Energy Systems Research

Volume 3 • Number 1 • 2020

Published by
Melentiev Energy Systems Institute
Siberian Branch of Russian Academy of Sciences

Available online: esrj.ru

ISSN 2618-9992

Energy Systems Research

Volume 3 • Number 1 • 2020
International scientific peer-reviewed journal
Available online: http://esrj.ru

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Energy Systems Research is an international peer-reviewed journal addressing all the aspects of energy systems, including their sustainable development and effective use, smart and reliable operation, control and management, integration and interaction in a complex physical, technical, economic and social environment.

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The journal is published by Melentiev Energy Systems Institute of Siberian Branch of Russian Academy of Sciences. The journal's ISSN is 2618-9992. There are 4 issues per year (special issues are available). All articles are available online on English as Open access articles.

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Contents

Causality-Based Policy Learning Frameworks Derived from Russian Power Sector Liberalisation

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***Abstract* — This paper is an inductive, qualitative case study concerning the development of new policy learning theory derived from Russian power sector liberalisation policy reform that was conceived and implemented from the year 2001 to 2007. The research extends the policy learning theory work of James and Jorgensen and others by more holistically explaining how policy knowledge, through policy learning, affects policy formulation, change, the direction of that change, and outcomes. To provide an investigative platform for this, the study aimed to capture the perceptions related to Russian policy learning and adaptation from three primary policy community groups which included Russian energy researchers, international industrial informants, and economists with a high degree of involvement in power sector liberalisation policy development. In the course of the research, policy learning causal 'moments' were identified in the form of synchronic and diachronic interrelated frameworks that indicated causal mechanisms and causal paths. The empirically derived research results were from conceptual, planning, and implementation processes used to diversify Russian policy learning, primarily from relevant, concurrent, international policy experiences and outcomes in Britain, and to a lesser extent, the USA.**

***Index Terms* — liberalisation, policy causality, policy framework, policy learning theory, power sector, Russia**.

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http://dx.doi.org/10.38028/esr.2020.01.0001
Received February 25, 2020. Revised May 01, 2020.
Accepted May, 17 2020. Available online July 31, 2020.

I. Introduction

The focus of the research was on Russian power sector liberalisation from 2001 to 2007 as a case study M. A. Lamoureux, "Policy Learning Theory Derived from Russian Power Sector Liberalisation Experience," Ph.D. thesis, Glasgow, Caledonian University, Glasgow, Scotland, UK, 2012, which was then analysed to outline and then identify new categories and frameworks in policy learning theory. The proposed power sector reforms identified in the case study were broad, complex and unprecedented in Russia, and were widely regarded as necessary to provide a better environment for investment and global energy integration. Russian policy stakeholders studied and utilised international models to craft domestic policies aimed at liberalising the power sector. However, the following was unclear:

1. the quality and mechanism of policy learning
2. the type, content, and application of policy learning over time
3. potential policy change and direction of change
4. outcome as a consequence of policy learning

Accordingly, the Main Research Question (MRQ) was: *What are the perceptions of three policy community groups, which include domestic energy researchers, industrial informants, and economists, regarding the formulation, change, direction of change and outcome of Russian power sector liberalisation policy?*

The literature review section describes conditions prior to liberalisation, and an overview of implementation status. The Russian and international liberalisation experiences are outlined. The methodology section describes the research method and techniques as well as the sampling method. The results section presents the synchronic and diachronic policy learning frameworks, including their causal, categorical 'moments' and relational properties. The discussion section presents the theoretical and practical implications of the frameworks in relation to extant frameworks. The paper concludes with a description of the policy theory implications of the research and recommendations for future research.

II. Literature Review: An Overview of Russian and International Power Sector Reform

A. Conditions prior to Russian power sector liberalisation

From 1992 to 2000 there were serious issues facing the power sector, such as, a significant decrease in capital investments for modernisation, and a sharp reduction in the commissioning of new capacity [1]. The power sector was being affected by the broader Russian economic crisis that:

"…created a very difficult situation in the industry. Inflation, non-payments, depreciation of assets, etc., interfered with the financial and economic activity of energy companies. All the indices of the industry gradually deteriorated and reached a critical level. The decrease in electricity consumption and high organisational and technical level of the [Unified Power System] UPS that had been achieved by the early 1990s somewhat mitigated the situation. However, the problem of equipment aging at power plants and networks grew increasingly urgent" [1].

Also, during this period, the power sector was largely a natural monopoly with vertically integrated companies having ownership of transmission, distribution, and generation functions [2].

In response to urgent problems in the power sector, the seminal law, *'About the Electric Power Industry'* was proposed and approved in 2003. This law was part of the development of a new legislative framework built in part upon external liberalisation experiences designed to enable general industry goals, such as, energy security for Russia; reliable functioning of the power system; and cost minimisation [1, 3].

B. Overview of Russian power sector liberalisation

Although there were several contemporary reasons for power sector liberalisation that will be examined infra, the roots of Russian power sector reform initiatives may run deeper and be causally connected to previous Soviet era attempts at "market oriented reforms" [4] under the category of an "experimental initiative" [4, 5]. The policy template for the power sector liberalisation initiative may have been formed under the previous Soviet system where reform "followed a broadly similar pattern of development (*it is perhaps more correct to identify a pattern of limited growth and decline*)" [4]. Soviet era reform, reflective of the description of Belyaev [1] supra, was focused on "particular industries or enterprises which have been experiencing specific difficulties…" [4].

Apparently in accordance with the approach taken with previous experimental initiatives, the Russian government developed medium and long-term economic policy reform programmes in 2000 and 2001 [6]. The two goals of the reform programmes were to increase private enterprise and investment [6]. The power sector represented the most serious problem for the Russian economy at the time because of inefficiencies and a deteriorating infrastructure [6]. Therefore, a primary goal for the sustainability of the infrastructure was to attract investment [7]. Linkages had been made between regulatory reform of the power sector, and the confidence of investors and potential entrants [6]. This vision of power sector restructuring included the de-integration of the Russian electric monopoly, RAO UES, and the ownership separation of the transmission network from distribution and generation [6]. Investment was a dominant internal motivation for Russian liberalisation of the power sector.

The liberalisation of the power sector in Russia should be conceived in the broader context of a transitioning economy, as well as policy development. A transitioning economy can be understood as evolving from a centrally planned economy to a market-based economy. In this context, the Russian power sector reform process was one element of an overall economic and political reform plan [8].

Russian power sector liberalisation was part of an international trend toward privatisation and liberalisation in the sector [9]. The Russian move to liberalise the power sector follows other international reform experiences led by Britain [10]. As such, power sector liberalisation was an innovative turning point for the evolution of the power sector toward establishing elements of competition [11]. It was posited that Britain, as an originator of power sector liberalisation policy, had that policy de-contextualised and institutionalised as global policy transfer occurred [12]. This was foreshadowed by Littlechild [13] who stated,

"In some respects, the circumstances of each developing country are different from Britain and from each other. Essentially the same principles of public policy apply… with appropriate modifications for the circumstances of each case, the policy of privatisation, competition, and independent regulation seems the right policy for developing countries too" [13].

This statement was indicative of subsequent international attempts to learn from and implement standardised power sector reform programmes which were patterned from Britain's leading experience [14, 15].

The Russian rationale for power sector liberalisation included internal motivations which, in addition to investment, included the need for higher levels of efficiency. However, there were external motivations as well, which included economic and technical interests. This was exemplified by Voropai and Kucherov, [16], who stated: "The goal of Russia and its Unified Power System (UPS) is to become an equal partner and major player in the European electricity market". This was indicative of European and (former Soviet) Russian interests in integrative energy cooperation [17,18]. Therefore, inasmuch as Europe followed the lead of Britain to liberalise electricity markets [19], and Russia had an interest in participating in the liberalised EU wholesale power market via transmission interconnections [16], Russian policy makers were also reacting to external political and business interests. Similar external incentives for Russian wholesale power market liberalisation were found in Russian economic and technical linkages with the Commonwealth of Independent States (CIS) and Asia [20, 21].

Russian motivations for power sector liberalisation and reform created an environment where policy makers became interested in learning from previous experiences, such as in Britain, which were considered optimal [22]. Accordingly, the British liberalisation example provided a broad reform record of privatisation [23], regulation [13], competition [24] and innovative wholesale power market designs [25, 26]. Therefore, although future assessments would conclude that no single liberalisation example works in all circumstances [27, 28], Russian policy makers attempted to learn and integrate policy principles for the design and implementation of a liberalised power sector from Britain and other countries [29].

C. Policy learning from international liberalisation experiences

Russian power sector liberalisation policy can be tied directly to the effects of, and response to, the broader economic challenge faced by the country [30], however the application of reform was focused, rather than comprehensive as identified in this quote: "Russian policy makers have not taken a holistic view of the design of the energy markets. For these reasons, Russia has not evolved towards a new policy paradigm in all energy sectors" [31].

Although a broader implementation of liberalisation policy was not enacted in Russia, comprehensive and parallel sectorial liberalisation, especially with related industries, was a common theme found in other countries who have implemented reform programs prior to Russian implementation [31]. Regardless, external policy learning took place in Russia, and was part of the policy-making processes of power sector liberalisation. External experiences became objects of study in Russia, with the intent to compare and contrast the policy experiences in other countries with that occurring in, and considered for, Russia [32].

As the experiences of other countries became known and analysed, divergent views surfaced regarding the direction of power sector liberalisation policy, generally categorised as debates between the 'reformers' and 'opponents' [33] or characterised as 'reformers' and 'conservatives' by Yi-Chong [28]:

"Moderate reforms were also the result of the conflicts between 'reformers' who were determined to bring Russian industries in line with the West and 'conservatives' who were not willing to risk the reliable supply of electricity".

This debate was reflected in more than 10 conceptions that were posited as power sector liberalisation and industrial restructuring possibilities [34], many of which were rooted in liberalisation experiences learned from other countries.

"Russia is drawing on the international experience of liberalising the electricity industry, but it is nonetheless a long and complicated process. In addition, no well-defined system exists for creating an optimal electricity sector, as the results of liberalisation in other countries are controversial" [35].

This quote from Kurronen, [35] supra, encapsulates the fact that Russian policy-makers have studied international experiences from conception to implementation, but that apparently no external liberalisation experience or policy standard is a perfect 'fit' for the Russian context. In contrast, Pittman [10] observed that the core objective of Russian power sector liberalisation is very similar to external experiences:

"The goal of the [Russian] restructuring strategy is the same as that behind the application of this now-standard reform model in other infrastructure sectors in other countries: to replace, where feasible, the old regulated, state-owned monopoly enterprises with deregulated, privately owned enterprises, competing among themselves to operate and invest efficiently and provide outputs at the lowest efficient prices".

Much of the policy debate surrounding implementation of liberalisation was centred around the components of 'conceptualisation' based on external experiences, and its integration with the realities of the Russian power system, structure, and end goal which were modified over time. Although it is unclear regarding the actual quantity or quality of Russian external power sector liberalisation policy learning, the manifestation of domestic reform policy, its effects, and change have allowed for some visibility into the policy-making process.

III. Methodology

A. Research Method

Case study methodology was chosen as a best fit for the research based on the premises that a "…case study is a research strategy which focuses on understanding the dynamics present within single settings" [36] and that "A single case study is still a single-shot affair - a single example of a larger phenomenon" [37]. At the beginning of the research there was interest by the researcher to determine if the case under investigation could yield hypotheses or theories that may be externally applicable, which would need to be included within the limited research purview and subsequent results. The rationale for this was based on the inherent economic and policy influence that Russia had within the contiguous Commonwealth of Independent States (CIS) at the time [38], the increasing power grid integration with Europe [16], and subsequent cross-border influence on policy formation and implementation. However, after a deeper review of scholarly, case study research, the researcher determined that the "case study should be guided by the research question" [39] and that the MRQ could be answered more profoundly by focusing on the internal validity of the research to be undertaken. This decision was substantiated by Gerring [37]: "Often, though not invariably, it is easier to establish the veracity of a causal relationship pertaining to a single case (or a small number of cases) than for a larger set of cases." Therefore, the researcher determined that a single-case study, as opposed to a cross-case study would provide a better means to identify and investigate specific causality and change associated with it. Gerring [37] substantiated this further by drawing a contrast between cross-case studies and single-case studies:

"cross-case studies are likely to explain only a small portion of the variance with respect to a given outcome. They approach that outcome at a very general level. Typically, a cross-case study aims only to explain the occurrence/non-occurrence of a revolution, while a case study might also strive to explain specific features of that event - why it occurred when it did and, in the way that it did. Case studies are thus rightly identified with "holistic" analysis and with the "thick" description of events".

B. Choice of analytic induction

The process of discovering emergent theory arising from qualitative interviews was aided by the use of analytic induction [38, 39, 40, 41]. Accordingly, the researcher interpreted data [42] without developed hypotheses prior to the collection of data. The researcher collected and analysed perceptions that provided conceptual insight into the mechanics of policy learning inasmuch as "Concepts are developed inductively from the data and raised to a higher level of abstraction, and their interrelationships are then traced out [41]. Additionally, analytic induction is an approach where "…theory comes last and is developed from or through data generation and analysis" [42].

C. Sampling method

The researcher conducted 20 semi-structured, in-depth interviews, composed of 18 distinct participants and 2 follow-up respondents. The data samples were from respondents who comprised three issue-related policy community groups. The policy community groups were elements of a homogenous sample of a power sector liberalisation 'policy issue network' as defined by Rhodes and Marsh [43], and henceforth referred to as the 'policy network'. The selective and theoretical sampling was guided in part by the conceptual developments from the data that provided the first insight into emerging theory and frameworks. The concepts, and subsequent research direction provided guidance for the selection of additional interviewees. As the primary aim was "not to generalise to a population, but to obtain insights into a phenomenon, individuals, or events"…"then the researcher purposefully selects individuals, groups, and settings for this phase that maximise understanding of the underlying phenomenon" [44]. Individuals were chosen to be interviewed because of their prominence in the research area and because they were "information rich" [45].

The researcher's approach to both the initial method of interviewee selection and subsequent addition of interviewees was reflective of the works of Carlsson [46], and [47, 48, 49] in the area of policy networks.

Carlsson [46] stated that "the network perspective can be distinguished by its (a) non-hierarchical way of perceiving the policymaking process, (b) its focus on functional rather than on organisational features, and finally (c) its horizontal scope." In this statement, Carlsson [46] was attempting to build upon the assertion by Hanf and Scharpf [47] that "the term 'network' merely denotes, in a suggestive manner, the fact that policymaking includes a large number of public and private actors from different levels and functional areas…". Therefore, it can be assumed that, although a policy network has a purpose holding it together, it also represents a diversity of members focused on a single policy problem. Carlsson [46] also suggested that "policy networks can be regarded as a broad generic category" and "can be divided into numerous subcategories". Kenis and Schneider, [48] also posited that "A policy network is described by its actors, their linkages and its boundary." Building upon this, the researcher agreed with the salient, and contrasting point made by Jordan [49] when he suggested that "the policy network is a statement of shared interests in a policy problem." A policy community, as a sub-set of the network, was defined as a group of "actors within the network" [50]. Hogwood in Jordan [49] further defined policy community as a concept describing "shared experience, common specialist language, staff interchange, and frequency and mode of communication." Accordingly, the researcher identified and assembled a sample of a policy network composed of policy communities. The result was the identification and sampling of three emergent policy communities:

1. Domestic energy researchers (Russia)
2. Industrial informants (Russia and external)
3. Economists (Russia and external)

These groups shared a distinct community interest and perspective in power sector liberalisation policy and had active or passive linkages and participatory intersections to compose an effective sample of a policy network involved with Russian and international policy learning and power sector liberalisation. Within the communities, the researcher utilised these criteria for inclusion and exclusion:

1. A perspective relevant to the research question.
2. Prominence in their policy community area of interest.
3. Active or passive linkages to the policy network focused on Russian power sector liberalisation.

Consideration was given regarding the level of effectiveness of the emergent communities on policy decision-making. This consideration fed into the above criteria for inclusion and exclusion inasmuch as the communities were relevant, prominent, and clearly linked to the broader policy network that had effect on policy decision-makers. For example, the communities tended to be relationally self-supporting, and had impact on the direction and scope of power sector liberalisation policy in Russia. This relationship became clearer as the researcher conducted interviews and became more aware of the broad learning relationships that were taking place across the network sample. This was led in part by the scientific activity of the Melentiev Energy Systems Institute (ESI) in Irkutsk, Russia, which was directed toward determining the scientific foundations and mechanisms for the implementation of Russian energy policy at national and regional levels. Since 2001, the ESI has been a leader within the liberalisation policy debate in Russia, and has contributed to the formation, definition and activity of the policy network and subsequent communities involved with relevant policy research, influence and implementation. This is explicitly apparent in the ESI's role in hosting international conferences such as the 'Liberalisation and modernisation of power systems' conference that began in 2001. In addition to strengthening the human network involved in power sector liberalisation research, products of the ESI liberalisation conferences were subsequently collected. Published proceedings and policy recommendations were provided to Russian and international policy decision-makers and leading power sector business interests. In addition to the liberalisation conferences, the ESI led joint Russian-European Union (EU) policy projects in the areas of 'coordination, operation, and emergency control of EU and Russian power grids' and 'technological problems of liberalised electric power system control', - both of which were embedded in the Russian power sector policy debate and decision process.

With the ESI domestic researcher 'community' as an emergent leader of the policy network, additional research and interviews revealed the linkages that existed between the other communities and members of the network. Most of the industrial and economic community members were influenced in some way by the work of the ESI, either by attending ESI liberalisation conferences, receiving ESI liberalisation policy publications, or indirectly, by having a role in determining international power sector liberalisation trends.

Importantly, Marsh and Smith, [50] found that the view of policy decision-makers "was clearly shaped by the structures of the policy community" (p. 17), and that "policy outcomes were shaped by the policy process and the nature of the community" (p. 17). This finding by Marsh and Smith, [50] substantiated the researcher's rationale for identifying prominent policy communities involved in Russian power sector liberalisation debate, as a data source.

As a follow-on from the establishment of a method for sample selection, the researcher wanted to gather a broad range of perceptions from the distinct policy communities to provide a high degree of richness in accumulated data. Therefore, the researcher chose purposeful, maximum variation sampling [51; 40; 41] as a means to choose interviewees for inclusion. Realistically, the selection of interviewees in the three interviewee groups represented a balance between interview feasibility due to time and distance, response to interview requests, the need to gather diverse perspectives from prominent policy community members, and the terminus dictated by data saturation. This sampling technique, therefore, manifested itself in the range of selection of Domestic Energy Researchers within the context of their diverse fields related to the research question and their departments at the ESI; Industrial Informants as represented by their range of experience and policy community relevance (individual and corporate representation); and Economists by their approach to the subject and range of research or international experience with policy learning and adaptation.

Additionally, selective sampling [52] was used initially to enable conceptual development followed by the use of theoretical sampling [52] as concepts and themes provided insight into the choice of additional sampling. A meta-sampling criterion for all participants was their range of horizontal linkages to the policy network, that at its core would address the research question.

The researcher followed a criteria of qualitative data analysis by adhering to data saturation as a sampling and analysis mechanism for naturally terminating the collection of data samples. This was substantiated by a survey of applicable literature regarding data saturation, inclusive of definitions of saturation, qualitative data saturation experience, sample size analysis based on documented British Ph.D. theses, and principles of data saturation. Based the experience of the researcher, whereby the study reached a point in sampling where additional interviews did not yield new categories, the researcher was confident that the number of interviews, the quality and quantity of data, and its homogeneity, naturally defined a termination of sampling. The survey of literature substantiated this assessment of the researcher by clearly indicating that the number of samples collected to answer the research question and to reach data saturation exceeded the minimum documented and recommended samples for a qualitative study, regardless of the methodology utilised.

IV. Results

A. Analytical policy learning frameworks for Russian power sector liberalisation policy

Significant findings of the research were abstracted, analysed, and categorised in the form of diachronic and synchronic policy learning theoretical frameworks. The emergent frameworks are indicative of analytical induction which is teleological inasmuch as it is a search for an end point in theory which is intrinsic in character. Theory assumes the existence of, and the ability to, discover the essential character or nature of the object of research.

B. Synchronic policy learning theoretical framework

A synchronic policy theoretical framework emerged from the research findings that actualises and analyses policy 'in the moment'. The synchronic policy framework, as an ontological construct, is concerned with policy at a specific space and time, exclusive of policy antecedents. The theoretical framework can be applied as a means to actualise policy, in the sense of it existing objectively, as a teleological process, and to analyse policy at a specific space and time.

C. Diachronic policy learning theoretical framework

A diachronic policy theoretical framework was identified from the research findings that actualises and analyses policy 'over time'. The framework, as an ontological construct, is concerned with policy change 'over time', inclusive of policy antecedents. The theoretical framework can be applied as a structure to create policy, in the sense that it is the vertical causation of policy existence, as a teleological process, and to analyse policy 'over time'.

D. Analytical overview of the frameworks

Previous policy learning scholarship demonstrated that theoretical, directional policy frameworks can be empirically derived in the areas of policy transfer [53] and policy transfer analysis. This has also been true in the development of sub-group policy learning frameworks [54]. However, there was a lack of organic relationship, temporality and reflexivity built into all of these frameworks. The frameworks derived from the research findings demonstrate both an internal, and external reflexive process. The synchronic policy theoretical framework is introduced first, as a means to present the theory that emerged from the data. The synchronic framework was reified prior to attaining all of the data, inasmuch as it was treated as an abstraction that was substantially existing and was then used to reflexively analyse unorganised data and to develop the meaning and properties of theory. Therefore, the synchronic framework logically provides the presentational systemisation of the research data.

There is an intrinsic relationship within the synchronic and diachronic theoretical frameworks. The three sub-categories of the Synchronic framework are the *concept, planning* and *implementation* that emanate from the original policy noumenal ideation. The sub-categories are directional, and each is assumed by the precursor, although they have distinct starting points in the noumenal, conceptual starting point. An important new finding in the research was the emergence of not only a continuum, or planned process involved with power sector design, but the importance of including the core categories in every actualisation and application of policy change. Surrey [5] indicated that the power sector liberalisation process in Britain was an experiment, and the findings of the research indicated that due to the level of previous international experience, the Russian process integrated conceptualisation into planning and implementation. As the process was implemented, as a retention of experimental elements [4], circularity leads back to conceptualisation as policy is required to evolve. Therefore, synchronic and diachronic policy theoretical frameworks are reflective of the primary categories, relationships, and directionalities which have emerged from the research. The sections, infra, review the core categories, and formal sub-categories within the analytical construct of the synchronic policy theoretical framework.

The emergence of frameworks from the data has constructed categories which comprise policy phenomenon, policy substratum and policy superstratum 'meta-moments' which then existentially define or reflect an intelligible grounding in the form of the policy noumenon. Patterns which have emerged provide a teleological basis for policymaking inasmuch as policy learning is, in a philosophical sense, a phenomenal starting point for diachronic policy creation, and policy diffusion is the effect of policy learning. The research indicated that policy learning is an on-going, reflexive process which not only studies national and international

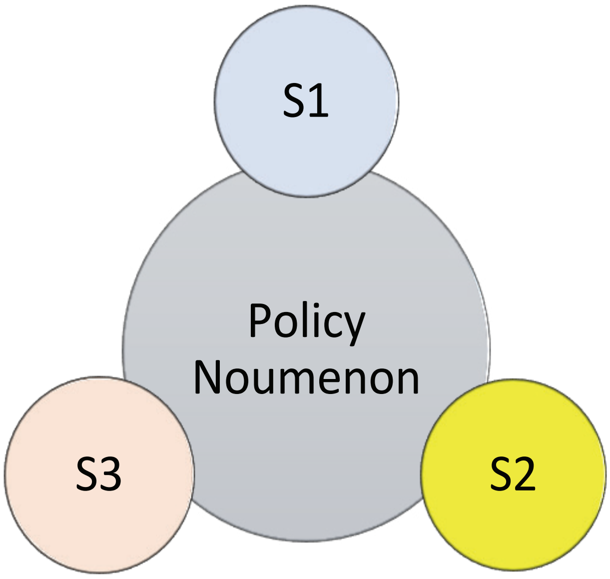

Figure 1. Synchronic Policy Framework.

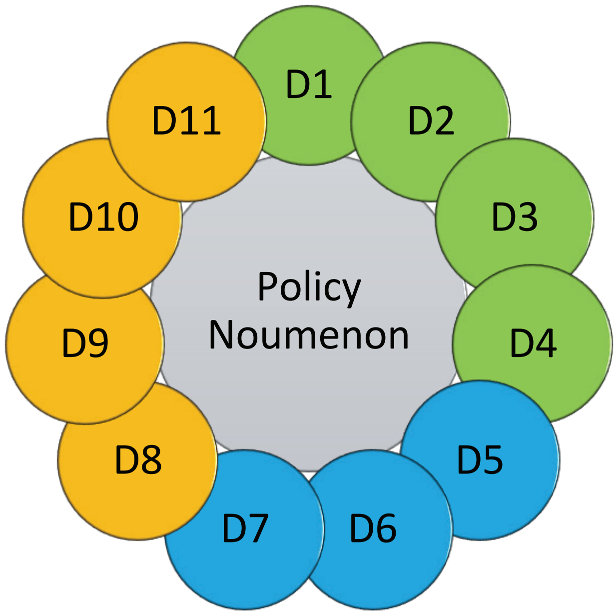

Figure 2. Diachronic Policy Framework.

policies, but also accounts for the praxis of the policy area under review or intervention. Policy learning, as a pro-active learning process, has a starting point which is an adaptation of policy and praxis, rather than transferential learning. Indeed, the research findings indicated that there can be variable conditions for policy learning inasmuch as contextual conditions vary according to national ethos and physiography.

Policy learning can be applied as a synchronic analysis method diachronically, which should measure micro and macroeconomic effects of policy during and after policy implementation. Policy diffusion, as a subset of policy learning inasmuch as diffusion occurs after policy learning, was found to be derived from multiple sources, at synchronic periods of time.

The emergent synchronic policy framework, as illustrated in Figure 1, infra, was used to analyse the diachronic policy outcome ‘in the moment’. Although the original Russian concept of power sector reform in favour of higher investment, as the starting point of the diachronic policy phenomenon is immutable, as it was created at a moment in the past, the synchronic policy phenomenon is mutable, as it is created ‘in the moment’. Russian policy makers have utilised the synchronic policy phenomenon cycle to measure the diachronic policy outcome against the original Russian diachronic policy concept, and on-going power sector conceptual developments outside of Russia. The categories in the frameworks relate to each other and relate to the distinct noumenon and phenomenon of emergent policymaking.

E. Synchronic policy theoretical framework moments relational properties: synchronic policy phenomenon meta-moment

S1. Conceptualisation

The research findings indicated that policy learning is formed by stages of activity. These stages are moments, in the sense that they are constituent elements of a complex process. Conceptualisation is inclusive of planning and implementation inasmuch as the latter two moments are objects of initial conceptualisation. Each moment, however, assumes the former, inasmuch as planning is a coming into being of a concept or set of concepts, and implementation is a coming into being of a concept or set of concepts and planning. This reasoning establishes the intrinsic relational circularity and extrinsic relational circularity whereby implementation is a means of re-conceptualisation ‘in the moment’.

Conceptualisation of policy provides for contextualisation in the sense that policy can be conceived within the endogenous context of policy implementation, but also in the context of exogenous applications. Policy conceptualisation is temporal in the sense that policy learning focuses on previous as well as on-going, extant policy examples. Policy formation has philosophical foundations with dialectical mechanisms, as a causal force, and is used as a remedy for perceived crises in an effectual sense. The effectual teleology involved with this suggests the need for reflexivity, inasmuch as supplying a remedy solicits an enquiry about whether the remedy can, or has, fulfilled the original intent. Policy implementation can be experimental, however, measurement of policy has higher validity ‘in the moment’ and has diminishing validity as predictive mensurative analysis is applied. This is particularly the case when the level of experimentalism is high, or where contextualisation of previous policy is significantly divergent from the original concept. Policymaking concepts include equilibria for policy outcomes, as well as short and long-term goals and macroeconomic outcomes dependent on the policy outcome.

Additionally, the crafting of conceptualisations should consider all short and long-term objectives to avoid a flawed concept, and a flawed policy outcome. Adequate compositions of policy subgroups should ensure thorough debate over all subject elements at the policy concept level. Policy conceptualisations should include assessments of current deficiencies as well as short and long-term policy effects. Policy conceptualisation has also included, as a precondition for policy success, on-going adaptation to change over time. This indicates that a legal structure should be in place to guide and analyse policy ‘in the moment’ to account for, measure and assess policy change over time. Importantly, policy conceptualisation should transcend the subject under study, and consider wider social benefits. Some areas of policy conceptualisation can be considered standardised, and some primarily contextualised. Standardisation should include the structural means for policy planning, implementation, and the creation of general guidelines.

S2. Planning

Conceptualisation of policy is a process whereby the basic outline of goals and predicted outcome are agreed upon. The planning moment follows the conceptual moment inasmuch as planning approaches the topic with more of an applied, logical thought process which is built upon knowing. Conceptualisation defines policy motivations, and planning centralises those motivations as the policymaking process unfolds. The end goal of policy implementation has a direct effect on the initial moments of policy conceptualisation and planning. If a policy goal is a transitional process, whereby the initial motivation will not be satisfied until a period of time has passed, other measures can be taken to encourage beneficial outcomes in the interim. This is explained in the research findings where policy solutions were categorised and implemented on different timelines. Policy planning should delineate all aspects required for policy implementation in the context of having a successful policy outcome.

S3. Implementation

Policy implementation can have planned and unplanned consequences. Such consequences can include internal problems which include delays and unforeseen influences which affect policy implementation and outcome

These consequences are effects of policy outcome. These effects can include negative outcomes which also can be categorised as policy devolution. This also indicates the need for regular assessments of policy outcomes, effects, and reconceptualisation to possibly revise the composition and direction of policy. The research findings suggested that there can be non-compliance of policy because of pre-existing conditions that make policy implementation impracticable. Policy evolutionary development and outcome over time requires a continual review and on-going learning process to detect unforeseen influences. Internal policy micro-developments can evolve, affecting macro-conditions, requiring a governing body to regularly intervene in policy outcome.

Section Summary

The research findings, at the level of inductive theory development, indicated that there is a directional linkage between policy conceptualisation, planning and implementation. Policy conceptualisation includes the conceptualisation of the planning and implementation process which should account for short and long-term policy goals. As policy is implemented, periodic assessment and analysis are necessary to detect or correct unforeseen evolution and devolution. As a consequence of policy analysis ‘in the moment’, the diachronic policy outcome can be re-conceptualised, and enter into a synchronic policy framework actualisation and analysis system.

F. Diachronic policy theoretical framework meta-moments and moments

The diachronic policy theoretical framework is composed of the meta-moments of *noumenon, phenomenon, substratum* and *superstratum*. As illustrated in *Figure 2*., the constituent, categorical moments are the stratal elements of the meta-moments.

A. Diachronic Policy Phenomenon Meta-Moment

The diachronic policy phenomenon meta-moment is the perceptible manifestation of the diachronic policy noumenon meta-moment. The noumenon provides the intelligible grounding of logical policymaking precepts. Although the noumenon in this sense holds a ‘place’ as a ‘moment’, it is a noetic cause that permeates the whole of the process. Therefore, noumenon is not delineated as a distinct ‘moment’. In contrast to the noumenon, the policy phenomenon is the perceptible event, circumstance or experience that provides grounds for, and stimulates, learning.

D1. Policy learning

Policy learning is composed of multiple sources of input, comprising policy diffusion. Policy learning is composed of both internal learning and external learning. Existing conditions are assessed in the policy learning process which include motivating factors and social and physiographic concerns. External policy learning provides perspective on internal concerns, as well as value attained through understanding previously conceived, planned and implemented policies. The research findings have indicated that policy learning precedes policy diffusion. However, prior to the assimilation of knowledge, policy information is imperfectly known, and mutated as the policy concept is learned.

D2. Policy transmutation

Policy transmutation is the process of learning extant policy in an imperfect way. The research findings indicate that policy is learned from endogenous incentives, or from exogenous developments. Policy networks have differing visions of policy conceptualisations, and that policy transmutation occurs as the policy concept is understood and contextualised to the receptor’s ethos. Transmutation of policy, as an imperfect understanding of policy, begins with the policy model under review. Policy transmutation, as a consequence of policy learning, begins at the point when policies under review are considered for adaptation.

D3. Policy trans-adaptation

Policy trans-adaptation follows a transmutation of an external policy concept. The external concept is not formed until a full concept has formed from policy learning, transmutation, trans-adaptation and diffusion. Trans-adaptation is the process and effect of policy learning of an imperfect concept. The process and effect are both individual and institutional. Trans-mutated policy concept may be flawed, or multi-dimensional, and subject to multiple points of view. Policy adaptation is subject to changing conditions. These changing conditions can be in the endogenous policy ethos, or by learning from the diachronic external policy ethos. Policy adaptation is the final step prior to policy diffusion, inasmuch as once the policy concept is imperfectly learned, thus mutated, and trans-adapted as an individuated idea or institution, policy diffusion occurs.

D4. Policy diffusion

Policy diffusion is a contingent process and effect. Diffusion is contingent on policy learning, transmutation and trans-adaptation. The research findings indicated that policy is diffused because of internal motivations or because of external impetuses. Diffusion of policy is primarily within the conceptual moment of policy inasmuch as it has not yet been manifested as a nomological process, such as a policy planning moment. The research findings indicated that the integration of external, diachronic policy with endogenous conditions, creates a policy coalescence. This policy coalescence creates a new concept which has originated from elsewhere but is developed from within. Therefore, at the full level of conceptual development, which is also the full level of the policy phenomenon, the next meta-moment of policymaking comes into being: the policy substratum.

B. Diachronic policy substratum meta-moment

The policy substratum meta-moment, composed of the stratal moments of a diffused, external policy concept, paradigm and network, is in relation to both the policy phenomenon, which is an event, circumstance or experience, and the policy superstratum. Inasmuch as the policy superstratum is the outcome, or substance of policy in the sense that it has independent existence and is acted upon by redundant causes, the policy substratum is the event or causes which act upon it; the changes occurring within it; and the attributes which inhere in it. The policy substratum is '*en prévision*' in the sense that it is in a state of readiness for the actualisation of policy outcome.

D5. Policy external concept

The external concept, as indicated by the research findings, is a fully actualised concept which was learned imperfectly, mutated and adapted to the endogenous ethos. As such, it is the starting event in the substratum whereby it comprises the policy paradigm and policy network. The external concept is the starting event that acts upon the outcome of policy. The external concept is the starting point for policy planning, as it provides a logical template for policy actualisation. The research findings revealed that once a concept is actualised, planning begins in the form of formulating structure and temporal, parametric considerations. The external concept is applied to the original motivating factor for the creation of policy. The external concept is paradigmatic, inasmuch as it is a pattern, example or model which effectively explains a complex policy process, idea or set of data.

D6. Policy paradigm

The policy paradigm emerges from the policy external concept. The policy paradigm is the external concept's lexical meaning inasmuch as the concept is the basis upon which the policy model is created. The research findings have indicated that the policy paradigm is composed of the external concept, and the endogenous ethos. The research interviews indicated that information which was learned was only relevant inasmuch as it pertained to the defined ethos in the context of policymaking. The policy paradigm addresses overall policy concerns which transcend the target policy area. The policy paradigm, as a more complete actualisation of policy, is reflective of the motivation for policy creation, and the process to actualise policymaking. The policy paradigm becomes the template for the creation of the policy network inasmuch as the policy network is a group or system of interconnected or cooperating individuals. The policy paradigm provides nodal interconnections for policy network activity in the sense that nodes are interconnected points of concentration which are actualised by the policy paradigm. To explain, arising from general policymaking motivations, a deductive process unfolds, whereby more specific areas of enquiry and actions emerge. These areas of concentration provide an indication of participatory enquiry and activity.

D7. Policy network

The nodal interconnections for a policy network begin prior to the policymaking process, as a network substratum, but only become fully actualised as a network once the policy paradigm is fully actualised. In this sense, one can logically comprehend that the first node, prior to the policymaking process, is the policy noumenon meta-moment. The policy network becomes actualised as the diachronic policy framework becomes actualised. In this sense, policy nodal interconnections evolve within the diachronic policy framework and provide the organic means of policymaking enquiry and activity. Policy nodal interconnections, as evolving policy networks, are organic in the sense that they are made up of systematically interrelated parts. The research findings have indicated that a policy network includes participants who are part of the endogenous ethos, and extraneous ethos, as long as the participation is relevant to the policy framework. The research findings indicated that categories of policy network participation exist. They are the inveteracy, who are established in the policy process over a long period of time, and the ephemeral, who either by policy framework design or external causation, interpose policymaking change for a brief period. The policy networks, as defined this way, can be individuals, groups, institutions, and referential ideas. Endogenous and extraneous policy outcomes are ideas that become part of a policy network. The policy network provides an actualisation for policy outcome 'over time' and 'in the moment'.

C. Diachronic policy superstratum meta-moment

The diachronic policy superstratum meta-moment, composed of the stratal moments of policy-networked actualised policy outcome, evolution, devolution and measurement, is causally contingent upon the policy substratum and the policy phenomenon. However, as the policy outcome interfaces with existence and time, and is then subject to evolution and devolution, it becomes independent of the policy substratum and policy phenomenon. The research findings indicated that the policy outcome can be a result, a consequence, but more importantly, a solution which is subject to change 'over time'.

D8. Policy diachronic outcome

The policy diachronic outcome has its basis in the policy network. However, prior to policy interface with existence, the policy outcome is more correctly to be considered a policy *dénouement*, in the sense that it is a proposed solution which needs to continue to unfold as it interfaces with existence. The *dénouement* is the final revealing of the policy solution as it is actualised 'over time' upon the policy target area. The policy outcome is the effect of policy 'over time' and 'in the moment'. The research findings indicated that either by design, or unexpectedly, policy can be applied in stages with the intent to phase-in the policy outcome. Therefore, the policy outcome is a diachronic process to reach the final policy goal and is also in a diachronic process as it reaches the policy goal. In this sense, the policy outcome is in an ever-changing state which is subject to the causation of the policy framework but is independent in the sense that it changes ‘over time’ as it interfaces with existence. The research findings indicated that both endogenous and exogenous factors influence the policy outcome. Logically, as the policy network actualises the policy *dénouement* and applies it to existence, the policy outcome is then in a state of ontogeny, in the sense that it has entered a life cycle subject to time and space, and therefore, evolution, in the sense that it is in a continual process of development.

D9. Policy evolution

Within the context of policy diachronic outcome, which is subject to space and time, policy evolution is a phylogenetic process. Policy evolution is phylogenetic inasmuch as it is the historical development of the policy outcome. The policy outcome is never quiescent and can only be measured in reference to its historical effect, and effect ‘in the moment’ which becomes less valid with change ‘over time’. The research findings indicated that policy evolution reveals positive aspects of policy implementation. Negative aspects of policy evolution can also be known. The research findings indicated that policy evolution is intrinsic to policymaking inasmuch as policy is subject to space and time, but also extrinsic in the sense that the policy external concept, as applied in the new ethos, can provide an evolutionary structure in the form of implementation stages. Additionally, the interaction of the synchronic theoretical framework promotes evolution based upon the measured amount of deviation or divagation from the original concept, or the need for deviation or divagation from the original concept because of empirical evidence which promotes such change. Any aspect of policy evolution which is measurably degenerative is categorised as policy devolution.

D10. Policy devolution

Policy devolution follows the emergence of policy evolution. As no policy is conceived perfectly, no policy can be implemented perfectly in the sense that policy cannot be complete in all respects, and without defects. Therefore, policy outcomes are subject to devolution whereby there is a degeneration of policy evolution. The research findings indicated that there can be intentional devolution of policy outcome. Additionally, policy devolution can take the form of unforeseen effects. These examples of policy devolution describe a process whereby the evolution of policy outcome degenerates from the original policy concept. The devolutionary process leads to a state of policy involution. Policy involution is a retrograde or degenerative change. The research findings have indicated that policy involution occurs after a period of policy devolution, particularly if the policy outcome framework was ill-conceived, and if policy intervention was non-existent or non-effective. From conception to devolution, policy measurement is a diachronic process. Policy measurement reaches a state of liminality, inasmuch as it is at a boundary or transitional point between two conditions, in the sense that it is optimally positioned between what is and what could be. This is also a liminal point between positive and normative aspects of policy. In this sense, policy measurement is circumferential.

D11. Policy measurement

Mensuration is intrinsic to policymaking in the sense that policy conceptions are formed by measuring a need. All aspects of the policymaking process are in relation to that initial measurement. The policy diachronic theoretical framework is reflective of the mensurative process whereby the need is addressed by conceptualisations and structures necessary for a remedy in the form of a policy *dénouement.* Once the policy *dénouement* is applied to existence, an effective mensurative process begins. The research findings indicated that once policy is implemented, a continual review of the policy is necessary, where policy devolution is measured. The research findings indicated that policy mensuration includes all aspects of policy creation and actualisation, including extrinsic policy change over time, and its relevance to the endogenous policy. The measurement of policy is at an optimal point between the relationship of the policy outcome, which is a dependent variable, and policy intervention, which is an independent variable.

Section Summary

Russian policy creation and application can be conceived as an expanding sphere with a centrobaric centre, in the sense that the policy noumenon provides an intellectual centre of gravity for the diachronic policy theoretical framework. The policy noumenon is also emanative, in the sense that the integrity of the noumenon is perceptible in the policy stratal moments. The stratal moments comprise the policymaking strata of policy meta-moments, the noumenon, phenomenon, substratum and superstratum. The moments of the policymaking framework are directional and represent an actualisation of policymaking elements ‘over time’. The diachronic policy framework provides the creation and implementation of policy ‘over time’, and the synchronic policy theoretical framework provides the analysis and actualisation of policy ‘in the moment’.

The interrelated frameworks, and their components, provide the basis of new theoretical policy learning findings derived from Russian power sector liberalisation policy experience. The next section builds upon this analysis and assertion by examining the noetic and phenomenal implications of the frameworks as well as a focused identification of where new knowledge is being applied with reference to relevant, extant literature.

V. Discussion

A. Gaps in policy learning theory and implications of the frameworks

In the course of examining literature related to policy learning during and after the period of research, the researcher became sensitive to a theme found amongst several articles and a book. This recurring theme identified a gap in research and knowledge, which, in turn, refined the focus of the MRQ. The following quotes provide references to a need to conceptualise, study, analyse (frame) the process and effects of policy learning in the context of policy implementation over time.

1. "Policy learning is a concept that is advocated but not adequately conceptualised" [55].
2. "the use of 'policy transfer' to explain 'policy change' and policy 'success' or 'failure' does not adequately separate the policy 'success' or 'failure' being explained from processes of 'policy transfer'"… "researchers may be better off using alternative theories focusing more directly on the effects of learning processes or styles of policy-making on policy outcomes" [56].
3. "In discussions of policy diffusion, particularly through the adoption of market reforms in the developing world, learning from the experience of others emerges as a plausible hypothesis, but it is clearly yet to be supported by empirical research" [57].
4. "Explanations of the policymaking process rest in theories and models, which should be, but typically are not, grounded in a framework" [58].
5. "…a deficiency of current policy theory is the inability to explain how policy knowledge affects policy formulation, change, the direction of that change, and outcomes" [59].
6. "The overarching concern is to understand how knowledge in the process guides our knowledge of the process and examining the utilisation of policy analysis and evaluation allows scholars to bridge the divide. There must be a 'perpetual 'back and forth' between images of the whole and particular details of time, place, and figure,' if policy scientists are to draw conceptual maps of the process and solve problems within the process" [59; 60].

Sabatier [61] indicated that The Stages Heuristic: "…divided the policy process into a series of stages-usually agenda setting, policy formulation and legitimation, implementation, and evaluation-and discussed some of the factors affecting the process within each stage. The stages heuristic served a useful purpose in the 1970s and early 1980s by dividing the very complex policy process into discrete stages and by stimulating some excellent research within specific stages-particularly agenda setting" (p. 6).

However, serious shortfalls were experienced with this framework according to Sabatier [61]: "It is not really a causal theory since it never identifies a set of causal drivers that govern the policy process within and across stages. Instead, work within each stage has tended to develop on its own, almost totally without reference to research in other stages. In addition, without causal drivers there can be no coherent set of hypotheses within and across stages" (p. 6).

B. Implications for policy actualisation and analytical functions

Once a policy is actualised, as a diachronic process, policy intervention 'in the moment' in the form of analysis and actualisation can take place. As a policy actualisation mechanism, the synchronic framework provides a means to:

- re-apply the intelligible grounding of the policy.
- have an interventional interface, to provide change in the policy according to its current existence.
- re-conceptualise, as an effect of mensuration.
- plan, according to the re-conceptualisation.
- implement, according to the re-conceptualisation and planning.

The analysis function of the synchronic framework inasmuch as it demonstrates the systematic enquiry of the life cycle of the policy as a single organism with component parts without reference to its antecedents. As a policy analysis mechanism, the synchronic framework provides a means to analyse the temporal life cycle of policy as a single organism. This includes:

- the condition and effect of the intelligible grounding of policy.
- the frequency and level of analytical interface with existing policy.
- conceptualisation status based upon current mensuration.
- the condition and effect of planning based upon the original conception.
- the condition and effect of implementation based upon the original concept and plan.

As illustrated in Figure 3., infra, the synchronic framework interfaces with the diachronic framework to

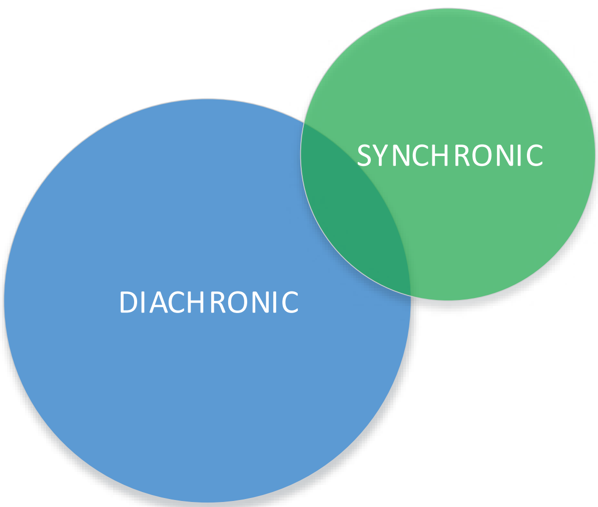

Figure 3. Synchronic and Diachronic Interface

provide actualisation and analysis 'in the moment'.

The diachronic framework provides a means to actualise and analyse policy 'over time'. The actualisation function of the diachronic framework demonstrates the actualisation of components 'over time'. Each level assumes the previous actualised moment. As a policy learning actualisation mechanism, the diachronic framework provides a means to actualise policy 'over time', in the sense that the original noumenon and phenomenon are immutable, as they exist in the past. As the diachronic framework moments become actualised, the policy outcome becomes independent of the original concept. The diachronic policy outcome becomes existential 'over time', and only becomes cognitively re-grounded when interfaced with the synchronic framework.

The diachronic framework demonstrates the systematic enquiry of the life cycle of the policy as a group of causally related moments. The diachronic framework is a mechanism to analyse the origin and evolution of the policy life cycle. The synchronic framework is dependent on the existence of the diachronic framework inasmuch as the synchronic framework becomes actualised when interfaced with an existing policy which was developed 'over time'.

C. Implications for policy theory and analysis

The effective importance of the synchronic and diachronic frameworks begins with the composition and integrity of the intelligible grounding of the policy phenomenon. The noumenon, as the intelligible grounding of policy, should dictate the perceptible moments of policy.

Policy theory was defined as "the total of causal and other assumptions underlying a policy" [62]. Additionally, the quality of a policy theory was posited, with assessable categories such as limitations, structure, and the means of evaluation [62]. These assumptions have led Hoogerwerf [62] to conclude that although there was an abundance of knowledge gained about the effects on policy "there has, however, been little research into the factors that determine the structure and the quality of policy theories. The determinates of the structure and the quality of policy theories may be found in:

(a) the political subculture
(b) the role of the person
(c) the nature of the political process
(d) the policy field; and
(e) the influence of new information" [62]

This statement, supra, and the previous assumptions about the phenomenon and quality of policy, make a vague intimation to the existence of policy intelligible grounding, and perceptible stratal moments, without coming to the full realisation of their conceptual existence, distinctions and relationship. This type of analytical vaguery is also found in literature regarding policy analysis [63]. Although perhaps strictly useful for existential cognition, public policy analysis was defined as "determining which of various alternative public or governmental policies will most achieve a given set of goals in light of the relations between the policies and goals" [63]. The implicit assertion made by this definition is that public policy analysis is disconnected from precognition, the endogenous ethos, and the phenomenal starting points of policy. The definition by Nagel [63] implicitly asserts that policy is an exogenous phenomenon, applied to existence as a means to reach a goal. It is interesting how Nagel's [63] definition is devoid of any reference to what is, but rather to only what could be: *the policy goal*. Even the intimation that there is a 'relation' between policies and goals is an implicit assertion that policy outcomes are not independent of policy concepts, and that 'relations' is an implication of causative separations between policies and goals which in effect are integral, constituent elements of the policy noumenon which are projected into the policy phenomenon. Some of the conceptual vagaries represented by literature surrounding policy theory and analysis were a consequence of the difficulties inherent in developing theories of public policy formation [64]. Indeed, "...public policy becomes troublesome as a research focus because of inherent complexity – specifically because of the temporal nature of the process..." [64]. As evidenced by the research, the temporal nature of the policy process is synchronic and diachronic in both actualisation and analysis. Importantly, Greenberg, et al [64] stated, "...improving our understanding of policy phenomena is clearly possible, if only through advancing the conceptual sophistication of theoretical formulations". There can be an advancement of conceptual sophistication inasmuch as "the collision between theory and data, while perhaps frustrating at first, can have important benefits for both researchers and theorists [64]. The reasoning from Greenberg, et al [64] is indicative of the temporal role of induction in theory formation. The policy analysis defined by Nagel [63] can be categorised as normative, in the sense that it focused on a goal, whereas the policy analysis as described by Greenberg, et al [64] can be categorised as positive, in the sense that it focused on what is existing in space and time.

D. The Frameworks 'fit' and relation to pre-existing frameworks

The frameworks are, at their essence, noetic with a noumenal projection into phenomenal experience and practical implementation. Perhaps most importantly for the understanding of the role, place and 'fit' of the frameworks is to distinguish them from existing, developed policy frameworks found in literature. The seminal article by Jenkin-Smith and Sabatier [61] identified the "textbook approach" (p. 175) also called "the Stages Heuristic" (p. 175) as the traditional policy framework model that has provided a long-term means for policy analysis. However, Jenkin-Smith and Sabatier [65] posited that the Stages Heuristic has outlived their usefulness because of apparent drawbacks. The frameworks identified in the research are not necessarily off-setting the existing and

Table 1. Comparative view of policy frameworks.

Policy Learning Frameworks	Description
Synchronic and Diachronic Frameworks	Noetic / Cognitive Phenomenal Intrinsically relational (two frameworks) Policy 'moments' with intrinsic causality Policy change in the moment and long term Policy learning in the moment and long term Dynamic Holistic focus Aggregate unit of analysis is abstracted conception
The Stages Heuristic Framework	Phenomenal Breaks policy process into standard sub-processes Lacks causality Lacks relational aspect between segments Focus on outcomes Top-down focus Limited to temporal unit of analysis
Advocacy Coalition Framework	Phenomenal Policy change over long periods Policy learning over shorter periods Focus on policy sub-systems Causal conceptualisations of public policies Aggregate unit of analysis is holistic policy domain (actors)
Institutional / Rational Choice Framework	Phenomenal Focus on individual institutions Assumptive of rationality in policy decision-making A-posteriori analysis justification of policy process rather than a-priori
Comparative Framework	Phenomenal External in scope Systematic approach by disaggregating external policy elements Aggregate unit of analysis is pre-existing policy model

well utilised policy frameworks, but instead provide a new, alternative, and systematic approach. This is established a-priori because all of the pre-existing frameworks are fundamentally phenomenal, without accounting for noetic and causal moments in the process. Table 1. below provides a comparative view of the frameworks when compared to the basic qualities and tenets of pre-existing policy frameworks. The reference to the Stages Heuristic and the Advocacy Coalition Framework draws particularly from Jenkin-Smith and Sabatier [65]. Reference to the Institutional / Rational Choice Framework is attributed to Ostrom [66] and the Comparative Approach Framework is attributed to Schneider and Ingram [67].

The authors, Jenkin-Smith and Sabatier [65] seem to begin to conceptualise the noetic aspects of policy learning and change by suggesting that "the principle glue holding a coalition together is agreement over policy core beliefs" (p. 183). Again, the authors refer to an aspect of a noetic framework without quite defining it: "…the only way to change the policy core attributes of governmental policy is through some shock originating outside the subsystem…" (p. 183). This could be interpreted as a reference to the synchronic – diachronic relationship of a policy learning framework. The depth of conceptualisation is limited at the insufficiently abstracted phenomenal level and perhaps inadequate use of words to convey meaning. An assumption based on a reading of literature can be made, therefore, that the frameworks derived from the research data are not related to pre-existing framework concepts, but they do provide a more abstracted and holistic means for policy learning and causal analysis.

VI. Conclusion

A. Policy theory implications

The finding of policy learning frameworks that were derived from indicators and themes in the data provides a means for a deeper understanding of actualisation and analysis of Russian liberalisation policy over time. The learning frameworks have implications for broader policy theory in the Russian context; Russian economic policy; and concepts of causation and change over time.

The frameworks hold internal and external validity inasmuch as they are derived and abstracted from intellectual and empirical data. The frameworks provide structure for international policy learning and discovery and have applicability in public and private sector policy actualisation and analysis.

The frameworks can be used to dissect and develop policy and associated theory 'over time', in the areas of policy intelligible grounding and quantification of the policy components. Policy theory is also further developed by the frameworks 'in the moment' in the sense that the clarity applied to the interface between existing policy and (re)actualisation of policy provides a means to reconceptualise an immutable first concept, based on measurable, empirical evidence.

The research findings support Littlechild's [13] general assertion that there are distinctions between countries, but the basic elements of liberalisation can apply to 'learning' entities with evolving, contextualised policy and implementation.

B. Recommendations for future research

With reference to Russian power sector liberalisation with infrastructural and policy tenet integration with external entities, the following four points are recommended for future research:

1. The degree and effects of internal 'coercive isomorphism' should be studied with the aim of examining the potential proportionate attenuation of policy evaluation and reflexive policy learning.
2. The effects of broad marketisation and institutional change over time on the implementation of micro-level power sector or networked industry liberalisation policy.
3. The dynamic relationship between adapting a meta-liberalisation policy in the power sector while physically integrating the power system with other countries with distinct, mixed-market policy directions.
4. Counterfactual studies of the power sector: structural, operational, and investment alternatives to liberalisation policy.

With a broader, theoretical view built upon some of the empirical findings, the following two points are recommendations for new or extended theoretical research:

1. The constituent and unified concepts within the policy learning frameworks are all opportunities for further research. The frameworks themselves are 'theoretical' and are elements of noetic and phenomenal criteria and parameters of policy learning theory. However, starting points for further theory development can be found in the frameworks' conceptual and relational properties and their interface with reality.
2. The frameworks, as a matter of policy validity verification, should be utilised as a means of analysing on-going Russian power sector liberalisation and other, international policy learning processes. Because of the nature of policy learning and change, it is possible that, given a longer period of time and additional resources, the components of the frameworks can change, and relational properties reassessed, along with a redefinition of policy learning and learning moments over time.

Despite the fact that power sector liberalisation policy experiences such as Britain's were frequently touted as international models to be emulated, the Russian experience with liberalisation policy change and direction of change, inclusive of causation, motivation, policy creation, policy learning, and implementation, indicated that although valuable, prominent international models cannot be wholly, successfully transplanted without being integrated with the political, legal and industrial realities of the learning entity. This finding, and its policy learning theoretical underpinnings, led to an identification of internally and externally valid, intelligible policy learning frameworks for the analysis and actualisation of public policy.

References

[1] L.S. Belyaev, *Electricity Market Reforms, Economics and Policy Challenges*. Springer: New York. 2011.

[2] S. Palamarchuk, and N. Voropai, "Status and Development of the Russian Electricity Market". *IEEE General Meeting*. Paper #09GM1410. Alberta, Canada: 2009.

[3] S. Palamarchuk, and N. Voropai, "Russia's Power Industry restructuring: Current State and Problems". [unpublished] Irkutsk, Russia: Energy Systems Institute. 2003.

[4] B. Arnot, *Controlling Soviet Labour: Experimental Change from Brezhnev to Gorbachev*. New York: M.E. Sharpe, Inc. 1988.

[5] J. Surrey, ed. *The British Electricity Experiment, Privatisation: The Record, the Issues, the Lessons.* London: Earthscan Publications, Ltd. 1996.

[6] Organisation for Economic Co-Operation and Development (OECD) (2002a) OECD Economic Surveys 2001-2002 Russian Federation. Paris, France: OECD Publications.

[7] G. Aslanyan, et al., "Monitoring the Sustainability of Russia's Energy Development". *Natural Resources Forum.* Vol. 29. 2005.

[8] B. Black, and A. Tarassova, *"Institutional Reform in Transition: A Case Study of Russia"*. Working Paper No. 237. Stanford: Stanford Law School.

[9] R. W. Bacon, J. Besant – Jones, "Global Electric Power Reform, Privatisation and Liberalisation of the Electric Power Industry in Developing Countries". Energy and Mining Sector Board Discussion Paper Series: The World Bank Group. 2002.

[10] R. Pittman, "Restructuring the Russian Electricity Sector: Re-creating California?" *Energy Policy*. Vol. 35. pp. 1872-1883. 2007.

[11] R. Eising, "Policy Learning in Embedded Negotiations: Explaining EU Electricity Liberalisation." *International Organisation*. Vol. 56, pp. 85-120. 2002.

[12] L. H. Pederson, "Transfer and Transformation in Processes of Europeanisation." *European Journal of Political Research*. Vol. 45, pp. 985 – 1021. 2006.

[13] S. C. Littlechild, Privatisation, Competition and Regulation in the British Electricity Industry, with Implications for Developing Countries. Joint UNDP. World Bank Energy Sector Management Assistance Programme (ESMAP): Washington, D.C. p. 4. 2000.

[14] T. Hori, T. "Creating the Wholesale Market for Electricity in Japan: What should Japan Learn from Major Markets in the United States and Europe?" *Centre for Energy and Environmental Policy Research*:

MIT. 2001.

[15] S. C. Littlechild, *Electricity: Regulatory Developments Around the World*. London: IEA/LBS. 2001.

[16] N. I. Voropai, and Y. N. Kucherov, “Russia and the EU Electricity Directive.” *IEEE Power Engineering Review*. (4). 2000.

[17] Energy Charter Secretariat (ECS). Conclusions Adopted by the Energy Charter Conference on 10th December 2003 with Respect to the Energy Charter Country Reports on Investment Climate and Market Structures in the Energy Sectors of the Russian Federation and the Slovak Republic. Brussels, Belgium: ECT. 2003.

[18] Europa, 2004a. Energy Charter. [online]. Europa – European Commission – Energy. Available from: http://europa.eu.int/scadplus/leg/en/lvb/127027.htm [Accessed 1 Jan. 2004] p. 2.

[19] R. Green, “Markets for Electricity in Europe.” *Oxford Review of Economic Policy*. Vol. 17 (3). 2001.

[20] CIS Electric Power Council. Current Status and Development of CIS Countries’ Power Sectors. Submitted for the Energy Charter Seminar “Liberalizing Trade and Investment in the Eurasian Power Sector”, 3 October 2002, Brussels. 2002.

[21] Asia-Pacific Economic Cooperation (APEC). Electricity Reform in APEC Economies –The Way Ahead. Peter Smiles and Associates, Resource Law International, APEC Energy Working Group. 2003.

[22] K. Vlahos, et al. “An Integrative Modelling Approach for Understanding Competitive Electricity Markets.” *The Journal of the Operational Research Society*. Vol. 49. (3). 1998.

[23] M. E. Beesley, *Privatisation, Regulation and Deregulation*. London: Routledge. 1997.

[24] Organisation for Economic Co-Operation and Development (OECD). Regulatory Reform in Gas and Electricity and the Professions. OECD Publications, Paris, France. 2002.

[25] S. C. Littlechild, “Competition and Regulation in the U.K. Electricity Industry (With a Brief Look at California).” *Journal of Applied Corporate Finance*. Vol. 13. (4). 2001.

[26] D. Newbery, *Regulating Electricity to Ensure Efficient Competition*. Cambridge: Department of Applied Economics. 2001.

[27] F. P. Sioshansi, “Sobering Realities of Liberalizing Electricity Markets.” *International Association for Energy Economics Newsletter*. Third Quarter. 2002.

[28] X. Yi-Chong, “The Myth of the Single Solution: Electricity Reforms and the World Bank.” *Energy*. Vol. 31, pp. 802-814. 2006.

[29] International Energy Agency (IEA) *Russian Electricity Reform, Emerging Challenges and Opportunities*. Paris, France: OECD. 2005.

[30] N. Ivashchenko, and L. Savchenko, “Restructuring the Russian Economy: Problems and Tendencies.” *Centre for Economic Reform and Transformation,* Dept. of Economics, Heriot-Watt University, Edinburgh.

[31] A. Belyi, et al. “Challenges to Russia’s Post-RAO UES Energy Paradigm: a Window of Opportunity for Sustainable Market Development.” *Journal of World Energy Law and Business.* Vol. 4. (2). 2011.

[32] O. Oksanen, et al., “Electricity Markets in Russia, the US and Europe.” *Proceeding from: 2009 6th International Conference on the European Energy Market EEM 2009*.

[33] V. Maslennikov, *Professor Victor Maslennikov, Director of the ‘Extreme Temperatures’ Institute of the Russian Academy of Sciences in Moscow*. Email interview. 2010.

[34] A. Abalmasov, and D. Kolodin, “Market Power and Power Markets: Structural Problems of [the] Russian Wholesale Electricity Market.” *Economics Education and Research Consortium*. Russia and CIS. 2002.

[35] S. Kurronen, Russian Electricity Sector – Reform and Prospects. Bank of Finland, BOFIT: Institute for Economies in Transition. 2006.

[36] K. Eisenhardt, “Building Theories from Case Study Research.” *Academy of Management. The Academy of Management Review;* 14, (4). 1989.

[37] J. Gerring, J. *Case Study Research, Principles and Practices*. Cambridge: Cambridge University Press. 2007.

[38] M. A. Lamoureux, “Economic Convergence Points of Russian, CIS and Asian Power Markets.” *Montreal: Paper published at the Power Engineering Society General Meeting, IEEE.* 2006.

[39] C. Marshall, and G. Rossman, *Designing qualitative research*, Thousand Oaks: Sage. 1999.

[40] M. Miles, and A. Huberman, *Qualitative Data Analysis*: *an expanded sourcebook*, Thousand Oaks: Sage. 1994.

[41] K. Punch, *Introduction to Social Research Quantitative and Qualitative Approaches*, London: Sage. 1998.

[42] J. Mason, *Qualitative Researching*, London: Sage. 2002.

[43] R. A. W. and D Marsh, “New Directions in the Study of Policy Networks.” *European Journal of Political Research*, 21: 181–205. 1992.

[44] A. Onwuegbuzie, and K. Collins, “Typology of Mixed Methods Sampling Designs in Social Science Research.” *The Qualitative Report*, Vol. 12 (2), June, 2007.

[45] M. Q. Patton, *Qualitative research and evaluation methods (2nd ed.).* Newbury Park, CA: Sage.

[46] L. Carlsson, “Policy Networks as Collective Action.” *Policy Studies Journal*. Vol. 28, (3). 2000.

[47] K. Hanf, and F. W. Scharpf, (Eds). *Interorganisational Policymaking*. London: Sage Modern Political Studies. 1978.

[48] P. Kenis, and V. Schneider, Policy network and policy analysis: Scrutinizing a new analytical toolbox. In B. Marin, and R. Mayntz (as.), *Policy networks, empirical evidence and theoretical considerations* (pp. 25-59). Frankfurt am Main: Campus Verlag. 1991.

[49] G. Jordan, “Sub-governments, Policy Communities and Networks: Refilling Old Bottles?” *Journal of Theoretical Politics,* 2 (3). 1990.

[50] D. Marsh, and M. Smith, “Understanding Policy Networks: Towards a Dialectical Approach.” *Political Studies Association*. Vol. 48, pp. 4 – 21. 2000.

[51] M. Gall, et al. *Educational research: an introduction*, White Plains: Longman. 1996.

[52] J. Morse, “The Significance of Saturation (Editorial).” *Qualitative Health Research*. Vol. 5. P. 147. 1995.

[53] M. Evans, and J. Davies, “Understanding Policy Transfer: A Multi-level, Multi-disciplinary Perspective.” *Public Administration*. Vol. 77 (2), pp. 361 – 385. 1999.

[54] M. M. Crossan, et al. “An Organisational Learning Framework: From Intuition to Institution.” *The Academy of Management Review*. Vol. 24. (3), pp. 522-537. 1999.

[55] P. May, “Policy Learning and Failure.” *Political Science*. Vol. 12 (4) pp. 331-354. 1992.

[56] O. James, and M. Lodge, “The Limitations of ‘Policy Transfer’ and ‘Lesson Drawing’ for Public Policy Research.” *Political Studies Review.* Vol. 1., Pp. 179-193. 2003.

[57] C. Meseguer, “Policy Learning, Policy Diffusion, and the Making of a New Order.” *The Annals of the American Academy of Political and Social Science.* Vol. 597. Pp. 67-81. 2005.

[58] C. Schlager, “A Comparison of Frameworks, Theories and Models of Policy Processes”, in: Sabatier, P. *Theories of the Policy Process*. University of California, Davis: Westview Press. 2007.

[59] T. James, and P. Jorgensen, “Policy Knowledge, Policy Formulation, and Change: Revisiting a Foundational Question.” *The Policy Studies Journal*. 37, (1), p. 141-162. 2009.

[60] H. D. Lasswell, “The emerging conception of the policy sciences.” *Policy Sciences*, 1 (1) pp. 3-14. 1970.

[61] P. A. Sabatier, (Ed), *Theories of the Policy Process*. Cambridge, MA: Westview Press. 2007.

[62] A. Hoogerwerf, “Reconstructing Policy Theory.” *Evaluation and Program Planning*. Vol. 13, pp. 285, 290. 1990.

[63] S. Nagel, “Conceptual Theory and Policy Evaluation.” *Public Administration & Management*. Vol. 6 (3). 2001.

[64] G. D. Greenberg, et al. “Developing Public Policy Theory: Perspectives from Empirical Research.” *The American Political Science Review*. Vol. 71. (4), p. 1532, 1543. 1977.

[65] H. Jenkins-Smith, and P. Sabatier, “Evaluating the Advocacy Coalition Framework.” *Journal of Public Policy*. Vol. 14, (2). 1994.

[66] E. Ostrom, “Rational Choice Theory and Institutional Analysis: Toward Complementarity.” *American Political Science Review*. Vol. 85. (1). 1991.

[67] A. Schneider, and H. Ingram, “Systematically Pinching Ideas: A Comparative Approach to Policy Design.” *Journal of Public Policy*. Vol. 7. (1). 1988.

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Assessing and factoring in investment barriers for making long-term projections of the energy sector

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***Abstract* — This study deals with the issue of a quantitative assessment of barriers to the energy sector development as an important stand-alone problem of making projections. To solve it, it is proposed to use iterative calcula-tions as performed by the system of optimization and stochastic models and factor in investment risks.**

***Index Terms* — projections, energy, economy, uncertainty, barriers, risks.**

I. Introduction

When making projections for the energy sector one has to consider multiple cases of its development as harmonized with the national economic growth scenarios, volumes, and the structure of exports and imports, the anticipated change in pricing, tax policy, and the governance framework. The growth rates of the energy sector industries as well as the speed of their structural changes that can be attained within each time period are limited, so arbitrary high demand for energy carriers proves impossible to meet. A possible bottleneck can manifest itself as a lack of time or that of materials, funding, and labor necessary for new capacity additions not in the energy sector itself but in its supporting industries.

Barriers are defined as existing bottlenecks that can potentially hinder the development of the energy industry under the conditions anticipated for a given time period. They are identified by juxtaposing the energy sector development requirements and the capacity to meet them. Quantitative estimates of barriers can serve as constraints in economic and mathematical models that are employed for making projections. The list of barriers should be tailored to a specific problem and a given hierarchical level. In doing so, it is reasonable to distinguish between constraints and barriers that are exogenous and endogenous to a given hierarchical level (system) (see Table 1).

The most significant internal constraints to be addressed while making projections of the energy sector are time barriers that are due to the inertia of the energy systems development. The latter manifests itself, in particular, as an inability to sharply increase production volumes within a short time period, to change the composition of facilities in individual industries of the energy sector as well as the makeup of the national energy balance.

Investment and resource barriers are also a serious obstacle to accelerating development, modernizing production, and adding new capacity. Investment barriers are related to price barriers and limited demand for energy carriers as financial resources required for making investments to a significant degree are a function of profits. In the case of individual energy companies and supplying companies, the market price may prove to be a barrier if it turns out lower than levelized costs (that is minimum acceptable supply prices that mark the threshold value below which the production and delivery of fuel and energy are considered to be uneconomical). The price barrier for a given energy carrier for the consumer arises in the case when its expected price proves unacceptable on economic grounds or for some other reasons and there is an alternative solution available.

High uncertainty of future demand and prices for energy carriers as well as the values of other input parameters result in challenges in estimating the return of prospective projects, especially in the cases of the valuation of development options for the energy systems of individual industries and regions. The larger the uncertainty, the higher investment risks, and the lower the probability of providing the required funding and other resources for planned new capacity additions. The combination of factors that are unfavorable for investors such as uncertainty, risks, insufficiently high performance, and time constraints may become a major barrier for new capacity additions in the energy sector industries. A valid quantitative assessment of this compound barrier is one of the important problems to be solved as part of making projections.

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http://dx.doi.org/10.38028/esr.2020.01.0002
Received April 06, 2020. Revised May 30, 2020.
Accepted June 20, 2020. Available online July 31, 2020.

Table 1. Constraints on the development of energy systems at different hierarchical levels.

Hierarchical level	Constraints	
	exogenous	endogenous
The national energy sector	Demand for energy carriers, limits on potential exports and imports of the energy sector products, prices on international and domestic energy markets, indicators of national security and energy security, limits on CO_2 emissions	Production volumes and development times of major centers of fuel production, the potential for new capacity additions in the electric power industry and the fuel industry
Regional energy sectors	Demand for fuel and energy, prices. Cross-regional energy links Environmental and social requirements	Proven reserves of fuel and energy resources, required time and volumes of new capacity additions in the electric power industry and the fuel industry within the region
Systems of individual industries	Volumes and patterns of demand for products of a given industry, potential for its exports, market prices, executive directives, terms of reference, and regulations.	The scale and required time for the potential development of mineral deposits and new capacity additions. Available capital expenditures. Availability and capacity of major transport links. Constraints on the development of individual companies (as applied to new capacity additions by regions).
Companies, businesses	Demand for company's products, market prices, export and import opportunities, competition, infrastructural constraints, executive directives.	Available production capacity (assets, technologies, labor, reserves). Financial resources. Performance of projects and their investment risks. The time required for construction and modernization

Note. The table presents the main constraints that are factored in the development, assessment, and choice of the options for developing the energy sector.

II. Incremental narrowing down of the uncertainty range of specified investment barriers

Taking into account the interdependence of barriers and improving the validity of their numerical evaluation are facilitated by an incremental approach that relies on the mutable mix of economic and mathematical models at different stages of making projections and at different hierarchical levels (Fig. 1).

The optimization models used when making projections for the energy sector can allow for the investment barriers in the assumed constraints on available capital expenditures or new capacity additions. They can be roughly defined and specified when using an iterative calculation scheme at the levels of the national energy sector, the electric power industry and fuel industry, regional power supply systems, and energy companies.

In the course of iterative calculations, the solutions obtained in optimization models of each hierarchical level get adjusted, and the specified constraints are refined. This changes the degree of aggregation of a geographical area, input data, and barriers, which increases when moving to a lower hierarchical level and decreases (gets aggregated) when moving the bottom-up way.

A non-exhaustive list of indicators linking the models of the energy sector, the electric power industry, and regional power supply systems is shown in Table 2.

At the lower level, the hierarchy of models can simulate the behavior of potential investors and determine financial performance and investment risks of new capacity additions to ensure rational energy supply to consumers in the area under consideration. For this purpose, it is reasonable to use a combination of optimization with the well-established Monte Carlo method [2]. A model (its software implementation) of this kind named MISS-EL was developed at the Melentiev Energy Systems Institute SB RAS [3]. It has all inputs specified not as point estimates, but as ranges of values with the indication of the nature of

Table 2. Main information links between models at different hierarchical levels when identifying and refining the information on investment barriers.

Hierarchical (model) levels	Degree of aggregation of the geographical area	Information to be obtained and refined	
		from the upper level	to the upper level
The national energy sector	Marcoregions	Demand for energy and exports of fuel and electricity. Fuel prices. The share of the energy sector in the total capital expenditures. Environmental requirements for the energy sector.	Adjustments with respect to fuel extraction, electricity production, and energy prices. Capital expenditures required by the energy sector. CO2 emissions. Estimates of sustainability and security of options of energy sector development.
Electric power industry	Federal districts, IEPS (interconnected power systems)	Constraints on fuel resources for power plants. Gas and coal prices for power plants.	Constraints on new capacity additions of nuclear power plants (NPPs) and renewable energy sources (RES). Cost of electricity generation and transport. Demand for fuel by power plants Required capital expenditures and strategic threats to electric power industry development.
Energy companies Regional energy supply systems.	Regions, wholesale generating companies, and territorial generating companies	Demand for electricity and heat. Constraints on gas supplies. Fuel prices. Constraints on cross-regional power transfers.	Investment risks of RES and other new power plants. Estimates of the energy security of regions. Share of distributed generation.

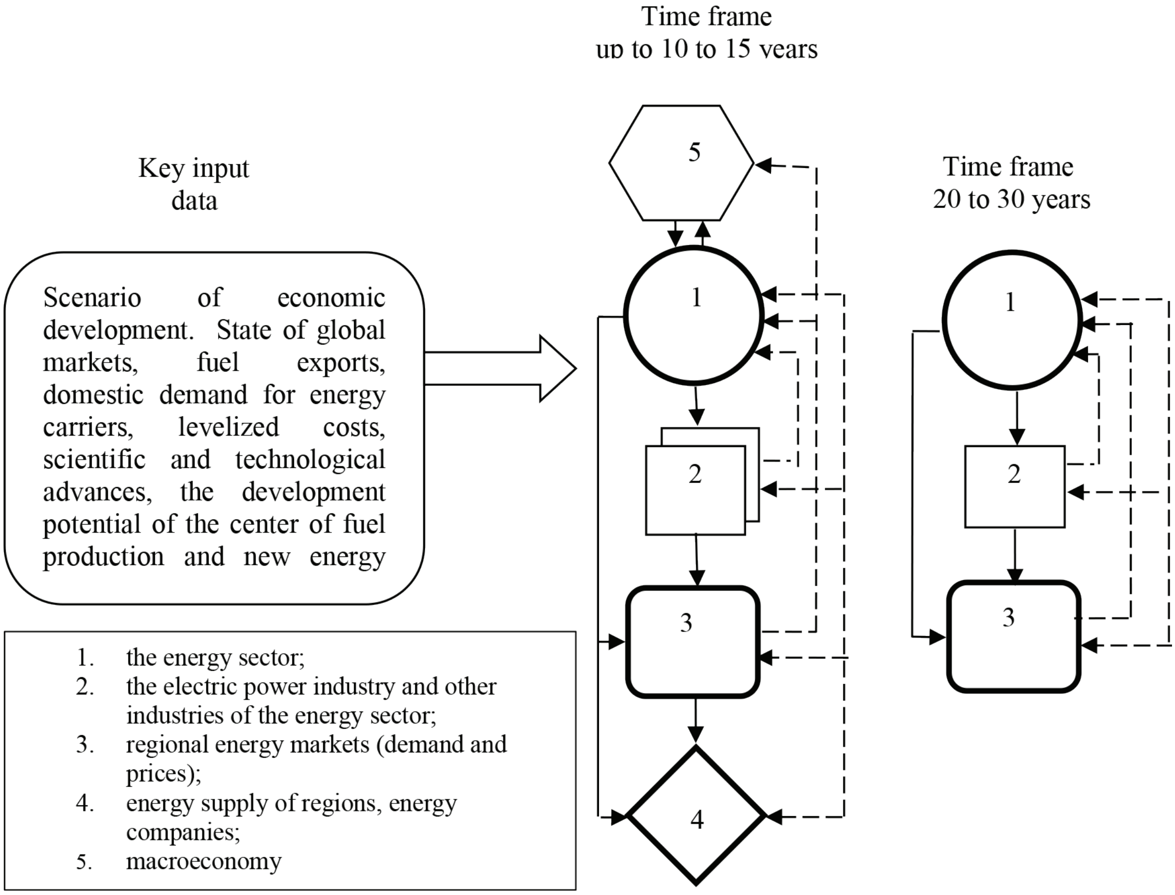


Figure 1. Relationships between models used in different stages of making projections of the energy sector [1].

probability distribution within such intervals. The adopted criterion of optimality is the minimum of discounted costs for electricity generation and transport.

Investment risks of individual groups of new power plants are determined by the frequency of their occurrence (with a certain capacity) in the solutions that are considered to be optimal under various conditions. The ratio of this indicator to the total number of solutions (hundreds of calculations) allows judging the probability of the implementation of the project of individual plants. The lower the probability the higher the investment risks.

The bottom-up calculations performed by the system of models allow consistent identification (adjustment) of investment risks of large-scale projects (at the level of energy supply of regions and energy companies), threats of the power shortage (at the level of an individual industry), constraints on new capacity additions in the energy sector and capital expenditures required for its development.

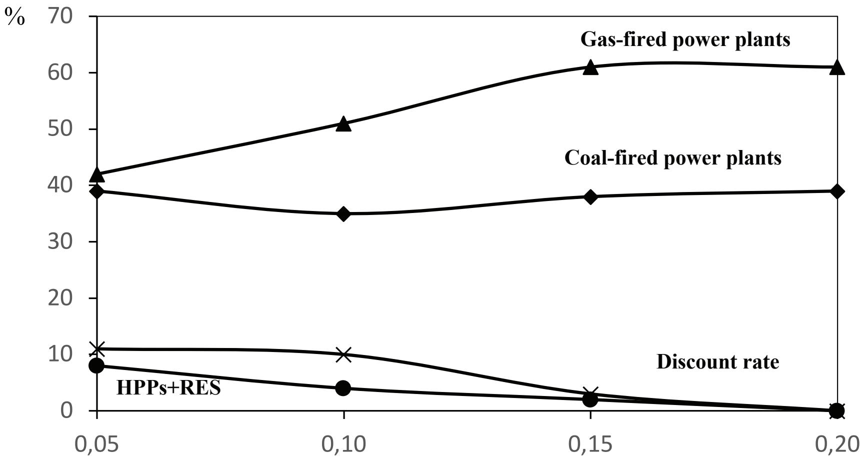
At the next iteration of calculations of the optimization model of the energy sector, its regional structure, and constraints on the new capacity additions that have unacceptably high investment risks can be changed. Directions and transfer capabilities of cross-regional energy ties may also be adjusted to mitigate the threat of a possible power shortage.

III. Impact of the Discount Rate on Investment Risks and Rational Mix of Power Plants

In the optimization models of the energy sector and the electric power industry, the criterion for rational choice is usually the minimum of discounted cash costs required to meet a given demand for energy carriers under given constraints.

In the planned economy of the USSR, normative coefficients of efficiency of capital expenditures were used to make annual operating costs and lump sum investment costs commensurate. The values of these coefficients were assigned separately for different industries, varying from 0.1 to 0.33 [4]. The highest values were applied to the chemical industry and consumer goods manufacturing, while the lowest values were used for energy and transport.

In a market economy, the economic performance of both individual investment projects and development options of entire industries is determined based on the net present value. Discount rates used to this end are a characteristic of the rate of return required by investors with respect to committed capital in terms of the comparable risk level of the investment object. They include two main components: that is, risk-free (guaranteed return on investment) and risky (risk premium) components. The numeric value of the former is mainly based on the base rate of the Central Bank



Note. Results of modeled calculations using the optimization (stochastic) model of power supply options for the European part of Russia under expected conditions for years 2025 to 2030.

0,05	0.05
0,10	0.10
0,15	0.15
0,20	0.20

Fig. 2. The effect of the discount rate on the mix of new power plants additions.

of Russia and currently amounts to 6-8% (net of inflation). In EU countries, the risk-free discount rate ranges from 1% to 7% [5].

The range of uncertainty of the risk component of the discount rate is significantly larger. The "Guidelines on the methods of the valuation of investment projects" [6] notice that the issue of specific numeric values of risk allowances for different industries and different types of projects has been poorly studied. According to these guidelines, the recommended values of these allowances are: 3-5% for investment in the development of manufacturing based on the mature equipment, 8-10% - for an increase in the volume of sales of existing products, 13-15% - for manufacturing and market promotion of new products, 18-20% - for investment in R&D and innovations. In investment projects that adopt a new technology under conditions of unstable demand and prices, it can reach 18% to 23% [7], and in some cases, it can be as high as 47% [8].

When deciding on rational options for the development of entire industries, rather than individual enterprises and companies, instead of commercial discount rates one should use social (fiscal) ones that factor in not only economic but also social, environmental, and other possible consequences of an investment.

There are no generally accepted methods for estimating the values of discount coefficients when optimizing the development of the energy sector and the systems of its individual industries. At the same time, as shown by model calculations as performed by the MISS-EL model, their value strongly influences the optimization results. As the discount rate increases, the relative efficiency and competitiveness of the most capital-intensive power plants (hydroelectric, nuclear, solar, and wind power plants) decreases. Accordingly, their share in the mix of the new capacity additions decreases (Fig. 2). The average generation cost in the given geographic area also rises: by about 30% when the discount rate changes from 0.1 to 0.2. Investment risks of projects of some power plants (coal-fired CHP plants and HPPs) do not respond so straightforwardly to changes in discount rates (Table 3).

Table 3. Dependence of investment risks on discount rate, %.

Power plant type	Discount rate			
	0.05	0.10	0.15	0.20
Gas-fired: condensing power plants	93	3.7	0	0
CHPPs	12	0.8	1	0.1
Coal-fired: condensing power plants	2	0.1	0	0
CHPPs	29	43	25	13
NPPs	11	27	90	99
HPPs	0.6	16	9	2
RES	5	68	100	100
The weighted average risk of new power plants in the aggregated region	22	8	4	2

Such a response is due to the fact that in the calculations there were no changes in constraints on gas supplies as well as upper limits of permissible cross-regional power transfers and new capacity additions of CHP plants and NPPs.

It is worth noting that the presented results of calculations are obtained given the normal distribution of input data within specified ranges of their probable values. In the case of interval (equiprobable) uncertainty, the value of investment risks is significantly higher (approximately twice that much).

Note. Results of modeled calculations using the MISS-EL model for one of the power supply scenarios of the European part of Russia (inclusive of the Urals).

Calculations and analysis of the principles and practices adopted in Russia and abroad enable us to propose the following approach to the assignment of the discount rate in optimization models used at different hierarchical levels and different temporal stages of making projections of long-term development of the energy sector:

- In the optimization models of the country's energy sector, the discount rate should reflect the social and fiscal significance of the compared options, and the value of the risk component should be less than that in the case of the optimization of the development of the electric power industry and especially the gas industry, taking into account the specificity of external and internal conditions and the significance of strategic threats.
- When optimizing the development of regional power supply systems due to particularly high uncertainty of future conditions, the issue of discounting proves particularly challenging. Therefore, the assessment of investment risks should be seen as a problem of its own and should be solved using the Monte Carlo method.
- The risk-free component of the discount rate, currently assumed to be 6-8%, should decrease with an increase in the projection time frame (to about 5-6%), and the risk component should increase (with an increase in uncertainty).

IV. Conclusion

The need for quantitative assessment of barriers and investment risks arises in various stages of making projections of the energy sector development. Such an assessment is needed to improve the validity of long-term projections, narrow down the range of uncertainty in development conditions, and identify possible challenges and strategic threats to energy security [10], [11].

Lack of financial and other resources may become one of the main threats of new capacity additions in the electric power industry and other systems of individual industries of the energy sector lagging behind the growing demand for them. Identification of the plausibility and significance of this strategic threat should be based on quantitative assessment of investment risks of both individual large-scale projects and options of the energy industry development of the country.

The proposed approach to a comprehensive assessment of investment barriers and risks assumes an incremental narrowing down of the uncertainty range in the energy sector development and the use of a system of optimization and stochastic models. Iterative calculations by these models at different hierarchical levels (performed in the top-down and bottom-up fashions) allow narrowing down the uncertainty range of possible dynamics of prices and demand for energy carriers. This, in turn, yields important information for the assessment of the performance and risk of large-scale projects and clarification of the required and possible capital expenditures.

Estimates of the riskiness of development options for energy systems should be reflected in energy security indicators. Some suggestions as to their mix are presented, for example, in [9].

Obviously, the rational ways of analyzing the projection range and assessing quantitatively investment and other barriers and risks depend on the time frame in question, the magnitude and nature of uncertainty of the input data, and the importance of the projection results for strategic decision-making.

Acknowledgments

The research was carried out under State Assignment III.17.5.2 (reg. No. AAAA-A17-117030310452-7) of the basic research of the SB RAS and was supported by t RFBR grant (Project No. 20-010-00204, No. 18-010-00176).

References

[1] Yu. D. Kononov. Approaches to improve the validity of long-term projections of the energy sector development. *Novosibirsk: Nauka*, 2015. 147 p. (In Russian)

[2] S. M. Ermakov. Monte Carlo methods and related issues. *Moscow: Nauka*, 1975. 472 p. (In Russian)

[3] Yu.D. Kononov, V.N. Tyrtyshny. Assessment of the impact of the nature of uncertainty in future conditions on the competitiveness of fuel supply options, *Energy policy*. 2011. No. 4. pp. 50-56. (In Russian)

[4] I.N. Yakovleva. How to calculate the discount rate and risk rate for a manufacturing enterprise, *Spravochnikhe ekonomista*. 2008. No. 9. pp. 24-33. (In Russian)

[5] Steinbach I., Staniaszek D. Discount rates in energy system analysis. Discussion Paper. *Fraunhofer ISI*, 2015. 18 p.

[6] Guidelines on the methods of the valuation of investment projects. *Moscow: Ekonomika*, 2000. 421 p. (In Russian)

[7] Yu.I. Zhdanov. The discount rate. The 10 modern methods of its calculation. Available at: http://www/finrr.ru/stavka-diskontirovaniya.html

[8] P.L. Vilensky, V.N. Livshits, S.A. Smolyak. Valuation of investment projects. Principles and practices. *Moscow: Delo*, 2001. 832 p. (In Russian)

[9] Yu.D. Kononov. Approaches to quantitative assessment of strategic threats to energy security, *Energy Policy*. 2014. No. 2. pp. 74-82.

[10]A.A.Makarov. Systems studies of the energy development: course of lectures. M.: *Publishing House of MEI*, 2015.280 p.

[11] A.A.Makarov and N.I.Voropai. Systems studies in the energy sector: methodology and results/ed. *M. ERI RAS*, 2018.309 p.

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Non-Isothermal Kinetic Model of the Methane Hydrate Dissociation Process at Temperatures Below Ice Melting Point

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***Abstract* — The paper proposes a new model of gas hydrate particles dissociation at high heat fluxes. In this model, the process of hydrate decomposition occurs under the conditions of competition between heterogeneous kinetics and gas filtration. An analysis of the experimental data gives new values of the kinetic coefficients for the hydrate dissociation at low temperatures. The calculation results make it possible to reproduce experimental data on the dynamics of methane hydrate powder dissociation (including dissociation under the conditions of gas burning above the surface) and to describe the phenomenon of self-conservation in terms of changes in the pore structure of the ice crust. The submodel of dissociation of a single particle is embedded in the mathematical model of transport processes in the powder layer, which allows analyzing the heterogeneity of heating and the collective effects of dissociation.**

***Index Terms* — natural gas, gas hydrates, dissociation, kinetics, heat and mass transfer, numerical modeling.**

I. Introduction

Gas hydrates are crystalline compounds formed by the interaction of gases with water at low temperatures and high pressures [1]. The wide interest in gas hydrates is due to their formation in natural and technical systems. For example, gas hydrate formation can be a problem during gas production in the cold season and its transport over long distances [2-4]. Estimates of the reserves of combustible gases bound in the hydrated form are very large, but the specificity of gas hydrates (dispersion, inaccessibility) does not allow them to be extracted.

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http://dx.doi.org/10.38028/esr.2020.01.0003
Received February 28, 2020. Revised March 19, 2020.
Accepted May 30, 2020. Available online July 31, 2020.

According to the energy forecasts in [5], [6], cost-effective technology for the extraction of natural gas from hydrate deposits will not emerge until 2040. In a recent review of the prospects for the energy use of gas hydrates [7], the authors estimate the start of commercial production no earlier than 2030. This is due to some technical problems, for example, low gas flow rates. Despite the widespread occurrence of hydrates on the seabed and in permafrost (estimates of reserves vary, but even pessimistic methods give multiple excesses of the "traditional" natural gas reserves), their volume fraction in bearing rocks is usually too small to provide a stable high gas flow rate [8]. An important issue is also the safety of production since during gas extraction hydrate-bearing formation changes its mechanical characteristics, which means that it can lose stability. Nevertheless, gas hydrate programs are intensively developed abroad. Note that the USSR and Russia have successful long-term experience in the extraction of methane from gas hydrate deposits in northern conditions [9]. At present, the average cost of methane gas hydrate exceeds the cost of traditional natural gas by 2–3 times. However, research and industrial projects in this area are quite intensive [10-12]. In addition to underwater drilling, the possibility of extracting hydrate from permafrost zones is being investigated.

Another important aspect of the energy applications of gas hydrates is storage and transport. The bulk density of the gas in hydrated form is higher than that for compressed gas, and storage conditions are softer compared to liquefied gas [13]. Under certain conditions, gas hydrates can exhibit abnormal stability, which is called self-preservation: at atmospheric pressure and slight cooling, the hydrate particles get covered with a crust of ice, which prevents the outflow of gas from the inner layers [14]. Maintaining hydrates under self-preservation conditions requires much less energy, and fire and explosion hazard is significantly reduced. Gas hydrate transport can be cost-effective at short distances and small volumes of supply [15, 16], for example, for supply to small power systems. Other hydrate applications may include thermal energy storage, desalination, gas treatment [17], etc. The stability of gas hydrates is an important issue, in particular, in the studies of the global climate. Methane is a greenhouse gas, and its natural emission includes, among other things, the decomposition of gas hydrates at seabed and permafrost [18]. To reliably predict the emissions, it is necessary to study the physicochemical features of hydrate dissociation under natural conditions. One way to use gas hydrates in the energy sector is to store CO_2 in gas hydrate deposits. Under a suitable combination of conditions, methane can be displaced from its hydrate form by carbon dioxide [19, 20]. Such technologies will reduce CO_2 emissions and control CH_4 emissions which, according to some geological models, can be dangerous (i.e. clathrate gun hypothesis [21]).

The existing problems of using hydrates are somehow related to an insufficiently complete understanding of the physics and chemistry of the processes that occur during the formation and dissociation of the hydrate phase [22, 23]. This, in turn, is associated with a variety of phenomena taking place during hydrate processing. Usually, the theoretical consideration of such processes employs simplified approaches. They simulate the propagation of the dissociation front with various moving boundary conditions [24, 25], or use diffusion models [26]. More detailed models take into account the formal kinetics of physicochemical transformations [27], heat and mass transfer in particles [28] and rocks containing hydrates [29].

One of the features of the dissociation of gas hydrates is a wide range of scales: physical and chemical processes occur at the level of hydrate cells (10-20 angstroms), clusters (of the order of nm), pores and cracks (0.1-10 microns), micrograins (0.1-1 mm), granules (1-10 mm), agglomerates (1-10 cm), and, finally, hydrate deposits (1-100 m).

Studies of the hydrate decomposition kinetics are possible only when sufficiently small (microns) particles are used [30]. There are also known studies, in which the molecular dynamics of the processes of decomposition and formation of gas hydrates is simulated [31–33]. In reality, however, hydrate particles are much larger, therefore, in the study of their dissociation, transport processes must be taken into account. In this case, the nature of the diffusion process remains uncertain, since dislocation diffusion in the ice layer allows one to explain the dissociation rate only in deep self-preservation. At the same time, it is known that the ice formed in the process of hydrate dissociation differs in properties from the ice obtained by freezing pure water. As a rule, it has a developed microporous structure, which results from the difference in the molar volumes of ice and hydrate [34]. Therefore, it is natural to assume that the key process responsible for the release of methane from the particle is filtration.

Previously, the filtration process was often considered as limiting on the scale of the gas flow in a porous rock containing gas hydrate. In this case, the decomposition of the hydrate occurs when the corresponding thermobaric conditions are reached and is limited by processes on the scale substantially larger than the particle size [35–37], or kinetics of dissociation is given that does not take into account the structure of the particle [38].

Mathematical models of porous reactive particles are widely used in problems of chemical technology and combustion theory [39–43]. Chemical transformations in porous particles take place in catalytic processes and during pyrolysis and combustion of solid fuels. Despite the formal differences, there is a certain analogy between these processes and the decomposition of hydrates, which can be used in the theoretical analysis.

In the present research, a hydrate particle dissociation model is developed, taking into account the heat transfer of the particle with the environment and the filtration of the gas released during dissociation through the particle pores. The process of hydrate conversion into ice and gas is considered as a one-stage irreversible chemical reaction with the kinetic coefficients that are evaluated from an analysis of various experimental data.

II. Filtration-Kinetic Model of Dissociation of Thermally Uniform Gas Hydrate Particle

We consider a hydrate particle placed in a heating gas medium. Under suitable conditions (increasing temperature, lowering pressure), the gas hydrate reaches the stability boundary and releases gas (Fig. 1). Depending on the external conditions, the limiting factor may be heat transfer or mass transfer.

The mathematical model is built taking into account several simplifications and assumptions, namely:

- there are no impurities in the hydrate, and the dissociation products are pure gas and porous ice;
- the particle is considered spherically symmetric;
- gas hydrate dissociation is a one-stage irreversible reaction (association is excluded);
- dissociation front gradually moves from the surface towards the center of a particle;
- the temperature field in the particle is uniform;
- the gas pressure field in the particle pores is quasistationary;
- the impact of the Joule-Thomson effect is neglected.

At the initial moment, the mass of the particle is equal to the mass of the hydrate phase. The mass fraction of methane in the hydrate is denoted by B (for example, for methane, one can take B = 0.12. Then we can make the material balance equations for the components of the particle:

$$\frac{dm^H}{dt} = -\frac{r}{B} \tag{1}$$

$$\frac{dm^I}{dt} = \frac{1-B}{B} r \tag{2}$$

$$\frac{dm^G}{dt} = r - j_g \tag{3}$$

Here m is the mass, kg; indices H, I, G refer to hydrate, ice, and gas, respectively; r is the rate of gas formation during decomposition of the hydrate, kg/s; j_g is the loss of gas mass due to mass transfer with the environment, kg/s. The thermal conductivity of a hydrate particle is of the order of 0.5 W/m/K [44]. Therefore, at moderate heating rates, it can be assumed with good accuracy that the Biot number for particles of the order of 1 mm is quite small. To be accurate, it is also necessary to take into account the contribution of the endothermic process, however, assessment of these disturbances can be made later. For small Biot numbers, the particle can be considered as thermally homogeneous, i.e. one can assume that the temperature gradient in it is not significant. In this case, the problem can be simplified without considering the process of thermal conductivity, and we can write the equation of heat and mass balance in the particle:

$$\frac{dm}{dt} = -j_g \quad (4)$$

$$C_p \frac{dT}{dt} = \alpha S(T_{out} - T) - Qr - c_p^G (T - T_0) j_g \quad (5)$$

In equation (5), C_p is the heat capacity of the particle, $c_p{}^G$ is averaged specific heat capacity of gas, J/kg/K; m is the particle mass, kg; T is the temperature of the particle, K; T_{out} is the temperature of the surrounding medium, K; α is the particle heat transfer coefficient, W/m^2/K; S is the particle outer surface area, m^2; Q is the thermal effect of the hydrate dissociation, J/kg.

The last term on the right-hand side of (5) is associated with a change in enthalpy due to a decrease in the particle mass ($dH = d(hm) = mdh + hdm$). The change in particle mass is determined by the gas flow rate through the surface. We assume that the specific heat capacity C_p is additive in terms of components:

$$C_p = c_p^H m^H + c_p^I m^I + c_p^G m^G \quad (6)$$

The density and heat capacity of ice and hydrate are taken from published data [45, 46]. The mass and linear dimensions of the particle are interconnected by obvious geometric relationships.

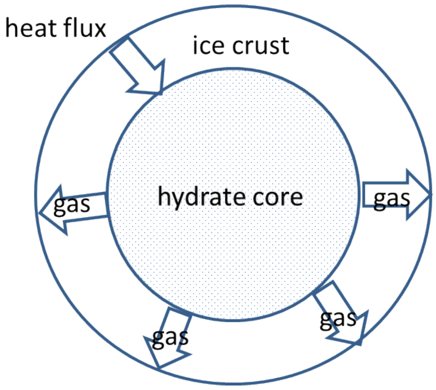

Fig. 1.The scheme of dissociation of a spherical gas hydrate.

The fraction of unreacted hydrate can be found from the gas mass balance:

$$X = 1 - \frac{\int_0^\tau r dt}{Bm_0} \quad (7)$$

From equation (7), we can immediately obtain the expressions for the mass of the solid components of the particle: $m^H = m_0 X$; $m^I = m_0(1 - B)(1 - X)$. In differential form, equation (7) can be written as follows:

$$\frac{dX}{dt} = -\frac{r}{Bm_0} \quad (7a)$$

Equations (4) and (5) are supplemented by the expression for the rate of the hydrate decomposition and gas flow from the surface:

$$r = k_0 e^{-\frac{E_a}{RT}} S_r \left(P^{eq} - P\right) \quad (8)$$

$$j_g = \rho_g S \frac{k_D}{\mu} \frac{P - P_{out}}{\delta} \quad (9)$$

In equations (8) and (9), k_0 and E_a are the pre-exponent factor and activation energy of the hydrate dissociation reaction, kg/m^2/Pa/s and J/mol, respectively; S_r is the area of the dissociation front in particle, m^2; P, P^{eq}, P^{out} is the current (intraporous), equilibrium and external gas pressure, Pa; ρ_g is gas density in the pores of the particle, kg/m^3; k_D is the permeability coefficient of porous ice; μ is the dynamic gas viscosity, Pa·s; δ is the effective thickness of the ice crust, m.

The equilibrium pressure of methane above the hydrate is usually expressed by an exponential function of temperature:

$$\lg\left(P^{eq} - \Delta P\right) = A_1 - \frac{A_2}{T} \quad (10)$$

Coefficients A_1 and A_2 can be determined from experimental data or theoretical estimation [47]. In this paper, the following values are accepted: A_1 = 4.77047; A_2 = 920.701; ΔP = 0.5. These values give characteristic features for the dissociation of methane hydrate: equilibrium temperature of -80 °C at 1 atm and equilibrium pressure of 25 atm at 0 °C.

To determine the gas density and pressure, it is necessary to know the pore volume in the particle. The hydrate porosity is usually very low, and due to the difference in densities during dissociation, ice is formed with a porosity of the order of 0.1. The volume of gas in the particle is very small, and the contribution of gas to the density of the heat capacity is almost invisible. With external heating, the dissociation of hydrate particles usually occurs layer by layer, and the decomposition front moves from the surface to the center. Given this, the surface of the dissociation front and the outer surface of the particle are connected by a relationship arising from geometric considerations: if we denote by X the fraction of unreacted hydrate (with respect to the initial amount), then the shrinking core model gives the expression for spherical particle:

$$S_r = S_0 X^{2/3} \quad (11)$$

Similarly, for the thickness of the ice crust, we obtain the expression (at linear approximation, i.e. for thin crust):

$$\delta = \frac{d_0}{2}\left(1 - X^{1/3}\right) \quad (12)$$

In equation (12), d_0 is the particle diameter. Thus, during dissociation, the area of decaying hydrate decreases, while at the same time the filtration resistance increases due to the growth of the ice crust.

Equation (9) models the Darcy filtration equation for the transfer of gas forced by pressure difference. In this case, a simplified form is adopted: the filtration rate is proportional to the average pressure difference in the particle, and the denominator in the expression for the pressure gradient is the thickness of the ice crust. Equation (5) is applicable to small X, when the change in the curvature of the dissociation front can be neglected. In a wide range of conversion degrees, we can consider the quasi-stationary problem [48, 49], then we can write:

$$\delta = \frac{d_0}{2}\frac{1}{X^{-1/3} - 1} \quad (13)$$

For a numerical study of the solutions to the system of equations (1–5), it is necessary to know the values of thermophysical and kinetic parameters. The most difficult parameter to evaluate is the permeability coefficient of porous ice. This parameter depends primarily on the size distribution of pores and their density. Following [50], it can be assumed that each pore can be represented as a cylindrical channel with an equivalent diameter equal to the average diameter of the pore. Then, the permeability coefficient for ice can be estimated as the total drag coefficient of pores per unit surface area of a particle. Assuming the laminar gas flow in small channels, we can write:

$$k_D = \frac{\Pi d_0^2}{32} \quad (14)$$

In equation (14), d_p is the average pore diameter, and Π is the surface porosity (total pore cross-sectional area per unit area of ice surface). The average pore diameter can be estimated from the studies where the hydrate surface was scanned using microscopy [14, 51] (hereafter, it is taken equal to 0.5 μm). In addition, an assumption is introduced that the average pore size does not change with the radius of the particle, which, of course, requires additional verification, but is applicable as a first approximation. Surface porosity is equal to the product of the surface pore density and the cross-sectional area of a single channel:

$$\Pi = \sigma \frac{\pi}{4} d_p^2 \quad (15)$$

In equation (15), σ is the surface pore density, m^{-2}. This parameter varies both under the influence of thermobaric conditions and under the action of mechanical stresses in the particle; its current value most likely depends on the particle heating dynamics. Evaluation of pore density is the most difficult task. At the same time, this parameter is most important for modeling processes such as self-preservation. In terms of the proposed mathematical model, this process is accompanied by a sharp drop in pore density. Thus, for closure, the model requires an additional equation for the pore density, which relates this quantity to the conditions of the dissociation process (temperature and pressure). Obtaining such an equation (even in the form of an empirical formula) is of scientific and practical interest. Since we do not have them at the moment, we have to use a simplified approach, namely, setting a piecewise constant pore density for different parts of the experimental curves. This approach is essentially adjustable, however, it allows obtaining several interesting results.

At the initial point $X = 1$, equation (9) is singular, therefore, for correct calculations, we assume that at the initial time moment $X_0 = 1-\varepsilon$, where ε is an arbitrarily small number (for example, of the order of the relative weighing error in experiments).

Preliminary studies have shown that to apply the model to explain the observed effects, it is also necessary to take into account in detail the conditions for the heat transfer of particles with external heat sources. Typically, in experiments, particles are heated by natural or forced convection of the airflow or combustion products (in the case of gas hydrates combustion), or by the heat flux passing through the wall of the vessel filled with hydrate. In both cases, there are characteristic effects of heat transfer in two-phase systems with phase transitions, as well as heat transfer in granular beds. The heat flux to a hydrate particle cannot be generally estimated simply by the temperature difference between the particle and the external environment: both the heat transfer coefficient and the local temperature difference (especially for the underlying layers of particles) in an unobvious way depend on the conditions specified in the experiment.

III. Low-temperature kinetics of methane hydrate dissociation

An important problem in hydrate dissociation modeling is the selection of reliable kinetic coefficients. At present, the published studies on the experimental measurement of the hydrate dissociation rate coefficient are very limited. This is due to some problems arising from such measurements: the mass transfer restrictions, the need to maintain isothermal conditions, self-preservation, etc. The results obtained by Bishnoi et al. [29, 52], where kinetic coefficients were measured for the dissociation of particles at temperatures above 273 K (which helped to avoid self-preservation) are most widely used. For negative temperatures, these coefficients, however, give a significant error, which may be due to differences between the mechanisms of "low temperature" ($t < 0$°C) and "high temperature" ($t > 0$°C) dissociation. The following is an attempt to clarify the values of kinetic coefficients for the region of negative temperatures and to generalize the known experimental data on this topic.

The present mathematical model of gas hydrate dissociation is based on the model of a shrinking-core and irreversible kinetics of dissociation in the Bishnoi form. It is supposed that the particle is isothermal. In this case, one can write:

$$\frac{dX}{dt} = -\frac{k_d^0 e^{-\frac{E_d}{RT}} \left(P^{eq} - P\right) S_0 X^{\frac{2}{3}}}{Bm_0} \quad (16)$$

Here X is the fraction of unreacted hydrate, the ratio of the gas contained in the hydrated form to its initial amount; k_d is the preexponential factor of the kinetic coefficient, kg/Pa/m^2/ s; E_a is the activation energy of the dissociation process, J/mol; P is the gas pressure in the pores of the particle; P^{eq} is the equilibrium gas pressure outside the hydrate particle; S_0 is the surface of the particle; B is the mass fraction of gas in the hydrate; m_0 is the initial mass of the particle.

For a spherical particle, we can write:

$$\frac{dX}{dt} = -\frac{k_d^0 e^{-\frac{E_d}{RT}} \left(P^{eq} - P\right) \pi d_0^2 X^{\frac{2}{3}}}{B\rho_0 \left(\frac{\pi d_0^3}{6}\right)} = -\frac{6k_d^0 e^{-\frac{E_d}{RT}} \left(P^{eq} - P\right)}{B\rho_0 d_0} X^{\frac{2}{3}} \quad (17)$$

For isothermal conditions, the entire expression written before $X^{2/3}$ can be considered constant, i.e. the specific dissociation rate increases with a decrease in the particle size, which is consistent with empirical observations. Complete decomposition of the particle is achieved at a finite time $\tau = 3/K$, where

$$K = \frac{6k_d^0 e^{-\frac{E_d}{RT}} \left(P^{eq} - P\right)}{B\rho_0 d_0} \quad (18)$$

The half-life will be equal to:

$$\tau_{0.5} = \frac{3\left(\sqrt[3]{1} - \sqrt[3]{0.5}\right)}{K} \quad (19)$$

The average half-life rate is:

$$R_{0.5} = \frac{0.5K}{3\left(\sqrt[3]{1} - \sqrt[3]{0.5}\right)} \quad (20)$$

To compare the data obtained under different conditions, it is necessary to take into account the temperature dependence of the reaction rate both for the kinetic coefficient (related to activation energy) and for the equilibrium pressure. The superposition of the temperature dependences of the kinetic coefficient and the equilibrium pressure can lead to a wide range of possible apparent temperature coefficients of the dissociation rate. Therefore, it is necessary to separate these factors with sufficient accuracy.

It is worth noting that the values of the kinetic coefficients are very sensitive to the choice of the equation for the equilibrium curve.

The kinetic coefficient can be determined in two ways: by the differential method (by measuring the rate of the process and comparing its values with kinetic models) and by the integral method (by measuring the characteristic conversion time).

Differential method

From equation (17) we have:

$$K = -\frac{X^{\frac{2}{3}}}{\Delta X / \Delta t} \quad (21)$$

where the numerator is the value of the kinetic function for the selected value of X, and the denominator is the average rate for a given moment in time, calculated as the difference approximation. For a constant heating rate, we have:

$$K = -\frac{\Delta T X^{\frac{2}{3}}}{\beta \Delta X} \quad (22)$$

where β is the constant rate of temperature change.

Integral method

Knowing the characteristic time, for example, the time of complete conversion or half-life (which can be determined more precisely), we can write:

$$K = \frac{3}{\tau} \quad (23)$$

$$K = \frac{3\left(\sqrt[3]{1} - \sqrt[3]{0.5}\right)}{\tau_{0.5}} \quad (24)$$

After the coefficient K is found, it is possible to isolate the component that corresponds directly to dissociation, according to (18):

$$k_d = k_d^0 e^{-\frac{E_d}{RT}} = \frac{B\rho_0 d_0}{6\left(P^{eq} - P\right)} K. \quad (25)$$

The pre-exponent and activation energy can be determined by constructing a regular Arrhenius plot in the coordinates $\ln(k_d) \sim 1/T$.

The two main sets of measurements that will be considered here are the data from [53] and [54]. Authors of [53] measured the relative intensity of the methane-water bond signal in samples of hydrate powder of different fractions at a constant heating rate of 1 K/min. The low rate of temperature change makes it possible to consider the conditions as isothermal between two consecutive measurements. Therefore, in this case, we can use the differential method, i.e. equation (21). In [54], the authors measured the average half-life rate of methane hydrate samples. The authors report possible temperature inhomogeneities, however, to a first approximation, we consider their experiments to be isothermal. The integral

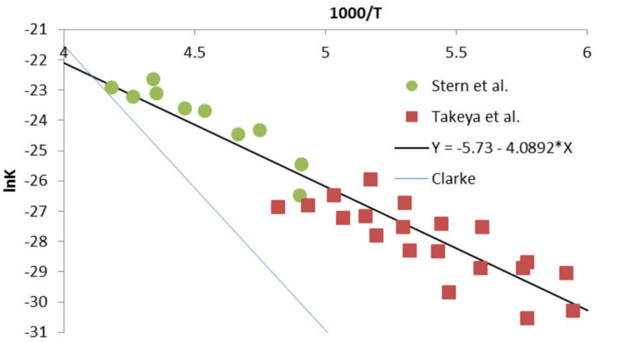

Fig. 2. Arrhenius plot constructed while processing the kinetic data [53, 54](the thick line is linear regression, the thin line is the kinetics of hydrate dissociation above 273 K [29]).

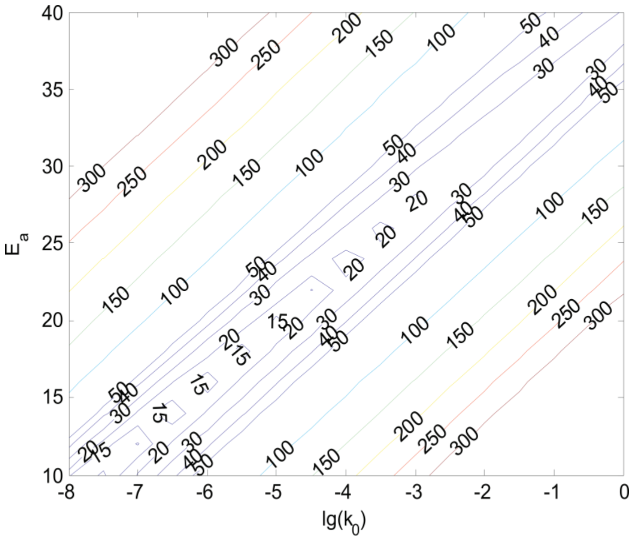

Fig. 3. The dependence of the residual function Φ on the values of the Arrhenius coefficients for the selected data set.

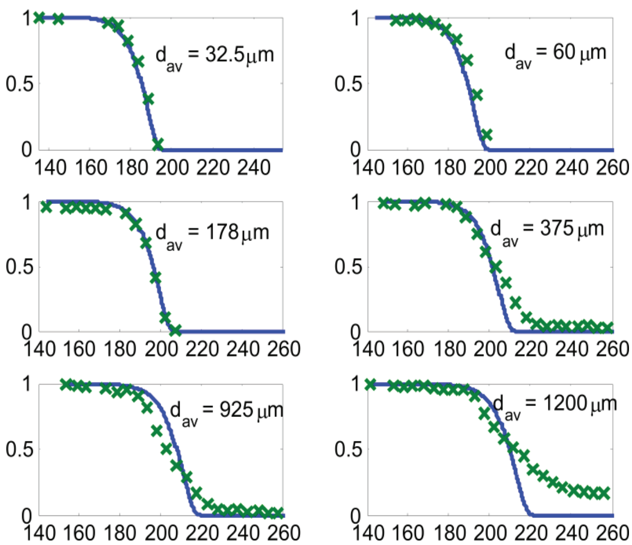

Fig. 4. Comparison of experimental and calculated kinetic curves of dissociation of methane hydrate fractions at a heating rate of 1 K/min [53]: solid lines — calculation, markers — measurements.

method, namely, equation (24), is well suited for processing these data.

Some experimental points are not suitable for analysis since, given constant P, equation (17) does not take into account self-preservation. According to the well-known literature data, this process begins at temperatures of the order of 240 K. Therefore, to isolate the kinetic coefficients without the influence of transfer processes, we have to exclude the temperature range from 240 K and higher. Nevertheless, there are still enough experimental points: 10 points from experiments [54] and about 20 from [53]. The processed results are shown in Fig. 2.

The average mass content of methane in the hydrate is assumed to be 0.12. The density of the hydrate is 910 kg/m^3. The average particle size for the data [53] is taken equal to the arithmetic mean for the boundaries of the indicated ranges. In [54], the samples were prepared by pressing a hydrated powder (an average size of 200–300 μm) into cylinders with an average porosity of 0.29. In this case, the hydrate particles most likely agglomerate, although they do not turn into monolithic samples (as indicated by porosity measurements). Therefore, the size of 10 granules of the initial powder was adopted as the characteristic size d_0.

Figure 2 shows that, despite significant differences in the experimental methods, the obtained kinetic coefficients quite well fall into a single dependence. The effective parameters of the Arrhenius form of the kinetic coefficient are equal to: k_0 = 3.25x10^{-5} kg/Pa/m^2/s; E_a = 34 kJ/mol. These values differ significantly from the kinetic coefficients from [29, 51], which may be due to the difference in the mechanism of dissociation. Interestingly, Clarke-Bishnoi (high-temperature) kinetic coefficient becomes larger than the obtained (low-temperature) values at a temperature close to 240 K (self-preservation starts here).

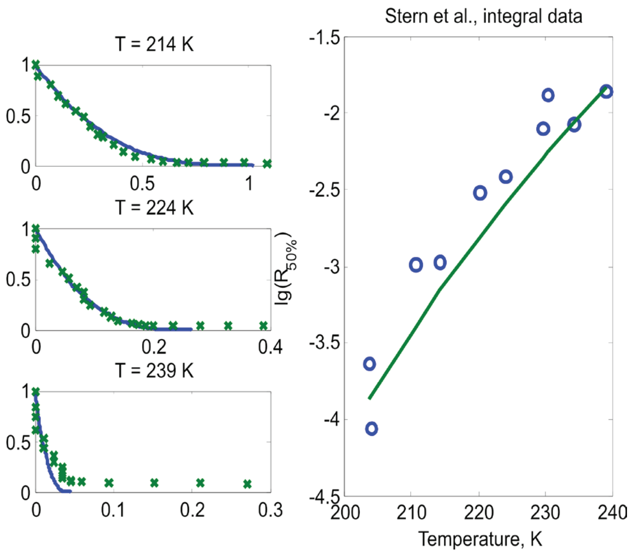

Fig. 5. Comparison of experimental and calculated data on the kinetics of methane hydrate dissociation (data [54]): (a) kinetic dissociation curves; (b) average integral half-life rate (solid lines — calculation, markers — measurements).

The estimation of kinetic coefficients from the measurement results is a typical inverse problem, the solution to which is not always unambiguous and stable. In this case, the solution was found by the least-squares method (search for the minimum of the non-negative residual function Φ):

$$\min \Phi = \sum_j \omega_j \left(Y_j^{exp} - Y_j^{calc} \right)^2 \tag{26}$$

Since the direct problem is nonlinear (especially in the non-isothermal case), and the set of experimental data includes experiments performed under various conditions, it is necessary to carefully select the weight coefficients for the residues obtained by approximating the kinetic coefficients for different options (heating rate, particle size, etc.).

The residual function includes discrepancies that arise when comparing the experimental and calculated data for four experimental sets: integral data [54]; isothermal kinetic curves [54]; non-isothermal kinetic curves with a constant heating rate [53]; non-isothermal kinetic curves with a varying heating rate [55]. In total, the residual function Φ includes about fifty terms. The results of optimizing the residual function in the space of coefficients k_0 and E_a are shown in Fig. 3.

One can see a region of parameters, where the pre-exponent and activation energy, varying over a fairly wide range, give approximately the same residues (the so-called compensation effect is observed). Therefore, for certainty in the calculations, the activation energy is taken to be 34 kJ/mol, as the generalized Arrhenius plot gives. The preexponential coefficient under these conditions is 0.019 kg/Pa/m^2/s. For these values, calculations were performed according to the data of [53, 54], the results of which are shown in Figs. 4 and 5. The calculated curves are in a very good agreement with the experiment for small fractions (up to about 200 μm). With a further increase in size under the experimental conditions, transport processes most likely begin to affect the kinetics of decomposition (for example, the resistance of the ice crust increases, which is one of the mechanisms of self-preservation [56]). Therefore, the decomposition of particles after reaching a degree of conversion of 50% is slower than expected from the kinetic model.

IV. Effect of particle sizes of gas hydrates on the rate of their dissociation

The granule size of a gas hydrate determines its outer surface through which heat and mass transfer processes occur, and the total amount of stored gas. From the simplest geometric considerations, it is possible to evaluate the qualitative dependence of the hydrate dissociation rate on the particle size, namely, small particles dissociate faster, $dX/dt \sim 1/d_0$. Such a simple dependence, however, will be observed only under isothermal conditions. If a gas hydrate dissociates at changing temperature, the dependence can change significantly due to nonlinear effects.

Equations (1–5) were numerically solved using a combination of explicit and implicit methods for ODEs. The equation for the kinetics of dissociation (17) is solved explicitly:

$$X^k = X^{k-1} - \tau K(T^{k-1}) \left(X^{k-1} \right)^{2/3} \tag{27}$$

Equation (27) gives the gas production rate r^k, the position of the dissociation front, and the ice porosity Π. Knowing these quantities, we can solve the difference equation of the gas mass balance (3):

$$m_G^k - m_G^{k-1} = \tau r^k - \tau \frac{k_D}{\mu} \frac{S}{\delta^k} \rho_G^k \left(\frac{RT^{k-1} m_G^k}{M_r V_G^k} - P_{out} \right) \tag{28}$$

The pore volume VG is determined from the geometric relationships: in the “shrinking core” model for the sphere $V_G = \frac{m_0}{\rho^H} \Pi (1 - X)$. The gas density ρ_G is specified iteratively (in most cases, however, an explicit approximation is sufficient). After all the components of the material balance are determined, the heat balance equation (5) is solved:

$$T^k - T^{k-1} = \frac{\tau}{C_p} \alpha S \left(T_{out} - T^k \right) - \frac{\tau}{C_p} Q r^k - \frac{\tau}{C_p} j_g c_p^G \left(T^k - T_{in} \right) \tag{29}$$

Equation (27) is an explicit Euler method formula, and equations (28) and (29) are written as an implicit form of Euler method. The numerical scheme was obtained by splitting the initial system into steps related to a chemical reaction, convective mass transfer, and heat transfer. Typically, such schemes have the first order of accuracy related to τ. In the calculations presented below, the time step was 10^{-4} s: such accuracy is sufficient for research purposes.

When considering the process of dissociation of a thin layer of gas hydrate, we can take the approximation of the reference particle [57, 58] and simulate the dynamics of the layer by the dynamics of dissociation of an individual particle. To test our model, experiments on the dissociation of a thin hydrate particles layer were carried out (the experimental technique is described in [55, 59]). Synthetic gas hydrate powder (mass fraction of methane 12%), poured into a metal tank with a layer with a height of 0.6 to 30 mm, was heated at atmospheric pressure and ambient temperature. In some experiments, the produced methane was ignited. Separate fractions (0.6 and 6 mm) and their mixtures were used.

The heat transfer conditions in the particle layer are rather difficult to establish with the necessary accuracy. In the experiment, the surface of the powder was controlled while the powder was heated by heat conduction through the walls of the tank, by the gas flow and the liquid water drainage, as well as flame radiation (in the experiments with hydrate combustion). Therefore, the heating of the layer was modeled by a constant heat flux. It was determined by the constant temperature difference between the particle surface and the gas at the heat transfer coefficient ($q = \alpha \Delta T$), which was estimated according to the recommendations for granular materials from [50].

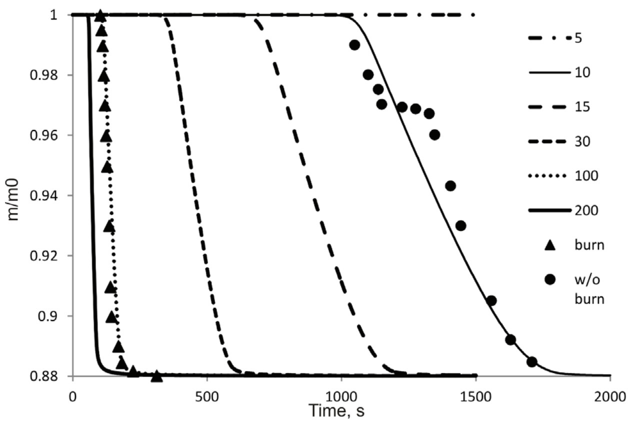

Fig. 6. Gravimetric curves of methane hydrate powder. Solid lines: calculation at different values of ΔT; points: experiment (triangles– with gas burning, circles– without gas burning).

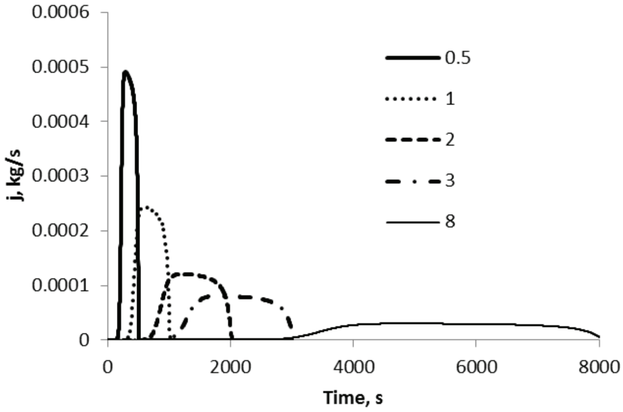

Fig. 7. The gas evolution rate during the dissociation of methane hydrate particles (numbers are average particle diameters, mm).

By varying the ΔT value in the calculations, we can find a suitable value for the experimental conditions. Under such conditions, the heat flux turns out to be a fitting parameter. The results of such a selection are shown in Fig. 6.

Hydrate dissociation without combustion of gas above particles is expected to occur more slowly due to a smaller heat flux. During dissociation with gas combustion above a layer, the temperature difference estimated using a mathematical model is about 100 K. It can be assumed that heat transfer occurs mainly between water vapor and melting ice on the surface of the particles. A high heat flux leads to intense heating of the powder; therefore, the hydrate passes rather quickly through the temperature region of self-preservation (240-270 K). The dissociation process without combustion is much slower. Therefore, in the experiment (circles in Fig. 6) a stepwise change in mass is observed: the hydrate particles remain in the self-preservation region for a time long enough to form stable ice crust on the surface. A model of the self-preservation phenomenon will be described in the next section.

The dynamics of methane hydrate dissociation with different particle sizes (reduced to the same mass) is shown in Fig. 7. Firstly, for the particles, the heating time to the dissociation temperature differs significantly: for small particles, heating takes time on the order of minutes, and for large particles, it takes tens of minutes. The peak dissociation rate also differs by an order of magnitude. Therefore, the dissociation and combustion of powders with different sizes of gas hydrate granules will occur in stages. Small particles are most reactive, however, their share in the powder depends on the method of hydrate production and processing (grinding, pressing, etc.). The production, storage, and transport of small particles are associated with additional energy costs and losses but the dissociation of large particles is much slower. Therefore, the question of the optimal fractional composition for different methods of gas hydrate processing is of interest. If the released methane ignites above the layer, then small particles could act as the initiator of dissociation.

V. Modeling the phenomenon of self-preservation of gas hydrate

The boundaries of the existence of gas hydrates are known with fairly high accuracy from direct measurements and models of chemical thermodynamics [1]. Self-preservation of gas hydrates is the abnormal stability of the hydrate in the region below the dissociation curve. The mechanisms of self-preservation are not completely understood [12]. It is known that the cause of abnormal stability is often an impermeable ice crust on the surface of particles. This crust can be formed both due to the liquid water contained in the system and due to the crystallization of supercooled water, which is formed during the hydrate decomposition [60, 61]. Surface microscopy shows that during self-preservation, the surface of particles is rearranged from a porous structure to a smooth continuous crust [62].

Using the molecular dynamics method, the authors of [63], [64] showed that the decomposition of hydration cells can be difficult due to the difference in the thermal expansion coefficients of ice and hydrate.

In [49], [65–68], the phenomenon of self-conservation is considered as a diffusion process with a damping diffusion coefficient (see also simplified diffusion-kinetic model with apparent mass transfer coefficient [69]). The author constructed an isothermal theory of self-preservation for particles of different geometries. Similar ideas were proposed in our studies [70, 71] of non-isothermal processes. A decrease in the transfer coefficients in a porous medium often means changes in its structure, namely, in the sizes and connectivity of cracks and pores of the ice crust. In this regard, it is interesting to study the relationship between the size and distribution of pores, and the dynamics of their change. The studies in [72, 73] proposed models for a developing pore system in carbonaceous fuels. It seems reasonable to use the available models for the inverse process associated with narrowing and blocking of pores [74, 75]. For example, exponent in time damping function used in [66], [68] is to have a

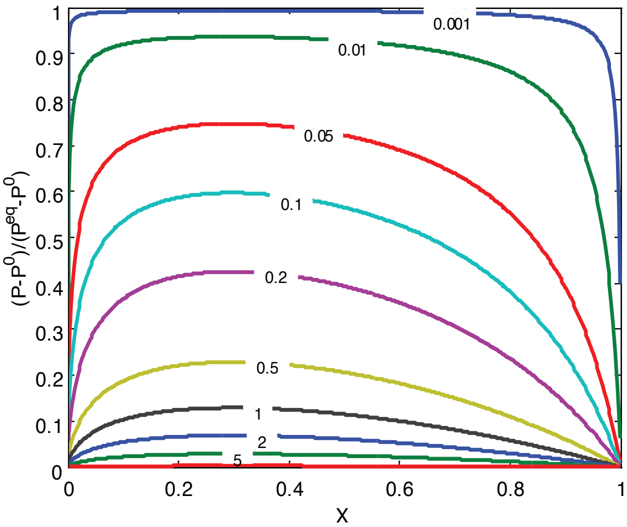

Fig. 8. The dependence of the solution to equation (30) on the fraction of unreacted hydrate X and the ratio k_F/k_R (values are shown on the corresponding curves).

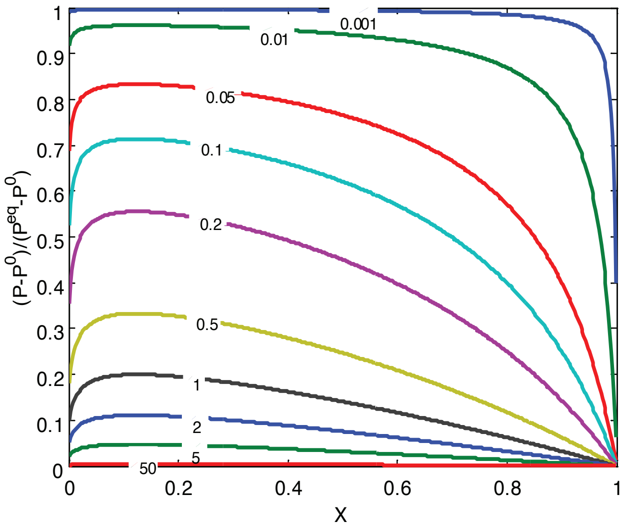

Fig. 9.The dependence of the solution to equation (31) on the fraction of unreacted hydrate X and the ratio k_F/k_R (values are shown on the corresponding curves).

physical sense related to thermomechanical properties of the ice crust.

Model (1–9) can be used to construct a qualitative theory of self-preservation based on the idea of varying permeability of the ice crust. Under the constant thermobaric conditions, we can write the equations for the stationary pressure in the pores of a particle (using thin crust approximation (11)):

$$k_R\left(P^{eq}-P\right)X^{2/3}-k_F\left(P-P_{out}\right)\frac{1}{1-X^{1/3}}=0 \quad (30)$$

For different values of the fraction of unreacted hydrate X, this equation gives different values of quasi-stationary pressure level. The natural parameter in this equation is the ratio of the kinetic coefficients k_R and k_F, which determine the rates of dissociation and filtration processes, respectively.

Applying stationary flow approximation (12), we obtain the following equation:

$$k_R\left(P^{eq}-P\right)X^{2/3}-k_F\left(P-P_{out}\right)\frac{1}{X^{-1/3}-1}=0 \quad (31)$$

The dependence of the dimensionless pressure in the pores of the particle on the ratio k_F/k_R and the fraction of unreacted hydrate X is shown in Fig. 8 for (30) and Fig. 9 for (31). The qualitative behavior of the solution does not depend on the approximation for the filtration resistance. With a high permeability of the crust, the pressure in the pores practically does not differ from the ambient pressure, however, even with comparable dissociation and filtration rate coefficients, the pressure increase becomes significant. The position of the maximum pressure can be determined by differentiating the expression for P with respect to X and equating the derivative to zero: the value of X at the peak of pressure does not depend on the coefficients k_R and k_F. Maximum pressure point $X_{max}$is equal to 8/27 for (30) and 1/8 for (31). Therefore, when using the thin crust approximation, we obtain peak pressure in the pores after the hydrated particle dissociates by about 70%. Given the spherical curvature of the particle, we obtain peak pressure in the later stages of decomposition (about 90%).

The self-preservation range may be considered as regions of low permeability curves in Figs. 8 and 9, when the pressure in the pores is close to the equilibrium value for a given temperature most of the conversion time. It can be said that the dissociation with self-preservation (at least in one of the variants of this phenomenon) is limited by filtration. With a sharp change in permeability, the solution moves from one curve to another.

The permeability of the ice crust, however, is uncertain. Its direct measurement is challenging, therefore, it is necessary to look for suitable assessment methods. As suggested above in (8), permeability can be considered (as a first approximation) in the form of a product of pore density and hydraulic resistance of a single pore. Then we need to measure the average pore diameter and their density per unit of surface. Both quantities, however, can change in the process of dissociation. Based on the surface microscopy studies of hydrates, the following values were taken: an average pore diameter equal to 1 μm and a pore density equal to 10^{11} m^{-2} (pores occupy about 8% of the surface).

In the region of self-preservation, the density and size of pores change quite sharply due to multiple local temperature inhomogeneities that cause phase transitions. Thus, a simulation model of self-preservation can be proposed: when a particle enters a chosen temperature range, its permeability characteristics drop to small (compared to the initial) values. In the calculations, this drop occurs stepwise, after which the permeability begins to increase (due to the development of cracks and thermomechanical stresses).

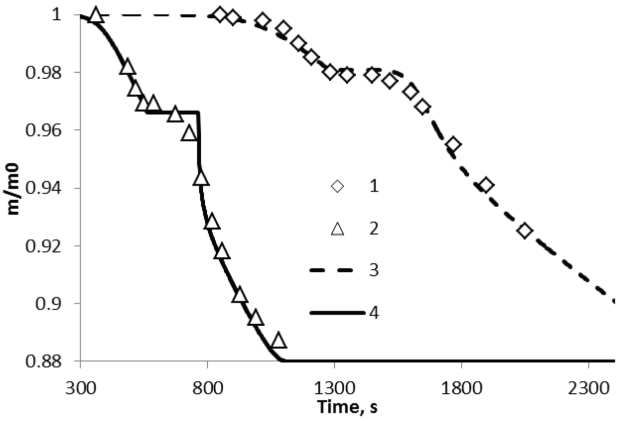

Fig. 10. Kinetic curves of dissociation of gas hydrates: 1 and 3 – natural gas hydrate; 2 and 4 – synthetic gas hydrate (lines – calculation, markers – measurements).

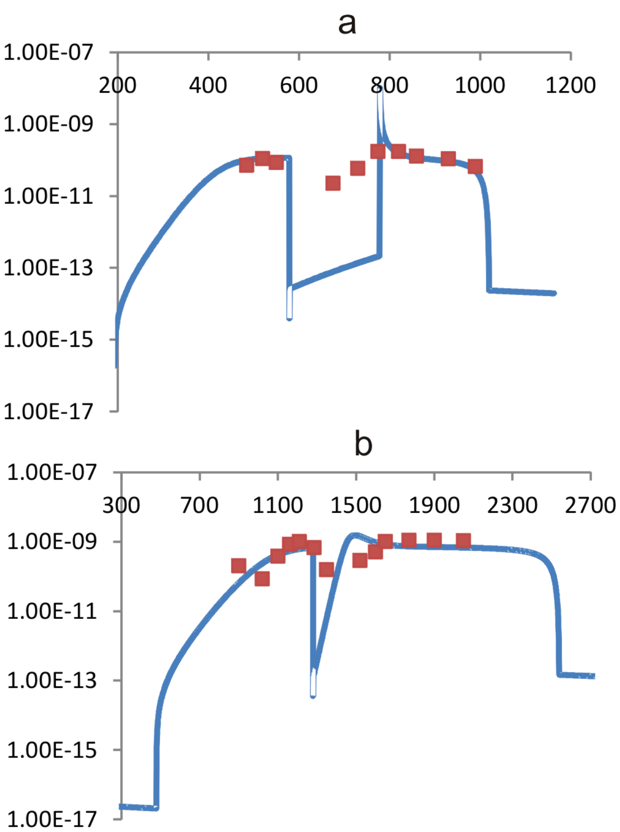

Fig. 11. Gas emission rate during dissociation of methane hydrate, kg/s: a – synthetic gas hydrate, b – natural gas hydrate (solid lines - calculation, markers – measurements).

To validate the mathematical model, dissociation of methane hydrate of different origins (synthetic and natural) was studied under the conditions of gas combustion above a layer of powder [76]. The average particle size was 1.2 mm for synthetic hydrate and 2.5 mm for natural one. The calculations were carried out for the experimental conditions, given permeability as a function of time. The comparison of the calculated and experimental data is shown in Figs. 10 and 11.

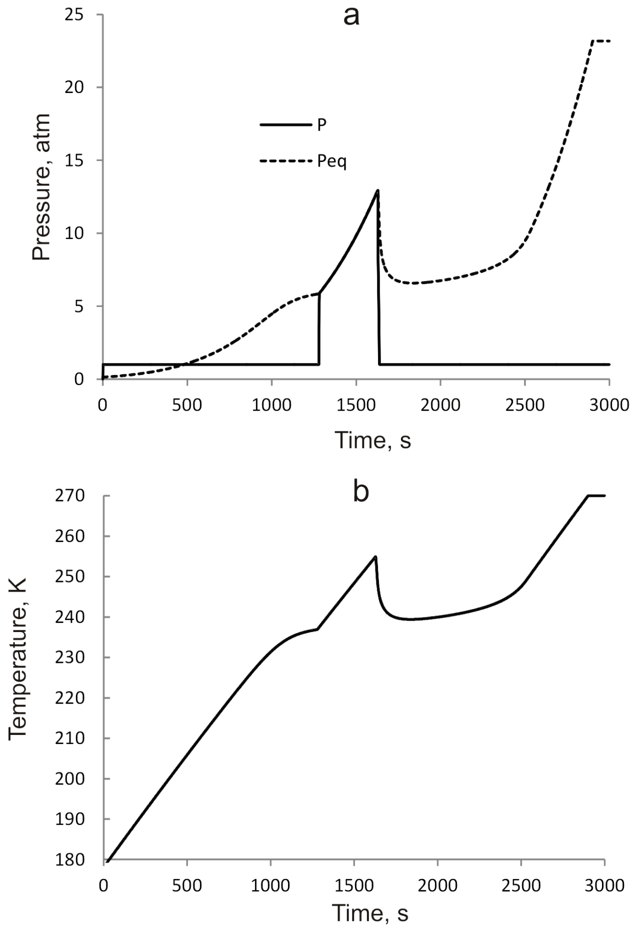

Fig. 12. Calculated parameters of dissociating artificial hydrate particle: a – pressure, b – temperature.

The change in permeability is specified through a change in the pore density (we assume that the pore size varies slightly under the experimental conditions). The initial density is 10^{11} m^{-2}, but when it goes into the region of self-preservation, it drops to 10^3 m^{-2}. The synthetic gas hydrate remains in the self-preservation conditions for a relatively short time, therefore, pore density in the calculation decreases and grows stepwise, which allows a fairly close reproduction of the measured kinetic curve (Fig. 10). Particles of natural gas hydrate are 2 times larger, so the duration of its decay, including the time spent in the self-preservation conditions, lasts longer. A stepwise change in pore density, in this case, gives high deviations; therefore, attempts were made to find a better approximation for the dynamics of permeability reduction. As the calculations show, the best agreement with the experiment is provided by a linear increase in the logarithm of pore density, i.e. exponential growth in the number of pores in time (Fig. 11). This dependence can be explained in terms of the development of random cracks.

The change in temperature and gas pressure in the particle can be seen in Fig. 12: when the site of self-preservation occurs, the pressure in the pores increases sharply, reaching equilibrium values, and dissociation

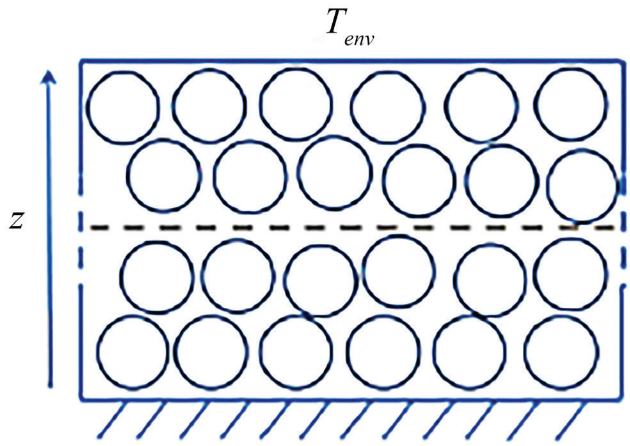

Fig. 13. Hydrate powder layer dissociation model.

practically stops. After returning to the initial permeability, the mass-loss rate becomes high due to the high rate of transfer processes after depressurization in the pores of the particle. In the case of natural hydrate, the rate of dissociation, taking into account self-preservation, slows down more smoothly, due to a larger particle size and, hence, higher filtration resistance of the ice crust (Fig. 11). Thus, using a fairly simple model with dynamic permeability, we can reproduce the phenomenon of methane hydrate self-preservation and study some details of this process associated with the internal state of the particle (apparent kinetics of dissociation, gas pressure in the pores).

VI. Mathematical modeling of dissociation of a gas hydrate layer in a one-dimensional approximation

The above calculations were based on the approximation of the thermal uniformity of particles and the possibility of representing the entire powder layer as a single particle. This approximation is applicable to thin layers, and with an increasing thickness (which is especially important for technological applications) it is necessary to take into account the inhomogeneity of heating along the layer height. It is especially important for the combustion of gas hydrates when temperature gradients could be large [77, 78]. In this section, we consider a problem in the one-dimensional approximation, where the spatial coordinate is the layer height. The problem statement is presented in Fig. 13.

A layer of powder of height L on a thermally insulated surface is considered. At the initial moment, the temperature of the powder is T_{in}, and the gas pressure in the porous space is atmospheric (P_{out}). Hydrate is heated by convective heat transfer from the ambient air with a temperature T_{out}. When the dissociation conditions are reached, the gas hydrate decomposes, and the released gas flows between the particles and leaves the powder layer. The perturbations introduced by the gas flow over the powder layer, the effect of self-preservation, and the influence of gravity are neglected. We use a single-temperature approximation (heat transfer between gas and particles occurs faster than heat distribution due to heat conduction and gas movement). Then the system of heat and mass transfer equations inside the layer is written as follows:

$$\left[C_p^g \rho^g \Pi + C_p^s \rho^s \left(1-\Pi\right)\right]\frac{\partial T}{\partial t} = = \frac{\partial}{\partial z}\left(\lambda_{eff}\frac{\partial T}{\partial z}\right) - \Pi C_p^g \rho^g U \frac{\partial T}{\partial z} + Q\frac{\partial \rho^s}{\partial t} \quad (32)$$

$$U = -\frac{k_D}{\mu}\frac{\partial P}{\partial z} \quad (33)$$

$$\frac{\partial \rho^s}{\partial t} = -K_d\left(P^{eq} - P\right)\rho_0^s\left(\frac{\rho^s - \rho_{end}^s}{\rho_0^s - \rho_{end}^s}\right)^{2/3} \quad (34)$$

Here P^{eq} is the equilibrium gas pressure above the hydrate at a given temperature, and K_d is the apparent dissociation kinetic coefficient, which is determined by the expression:

$$K_d = k_d^0 \exp\left(-\frac{E_a}{RT}\right)\frac{6}{Bd_p\rho_0^s} \quad (35)$$

The boundary and initial conditions are as follows:

$$P(0,t) = P_{out} \quad (36)$$

$$-\lambda_{eff}\left.\frac{\partial T}{\partial z}\right|_{z=0} = \alpha\left(T_{out} - T\right) \quad (37)$$

$$\left.\frac{\partial P}{\partial z}\right|_{z=L} = 0;\ \left.\frac{\partial T}{\partial z}\right|_{z=L} = 0 \quad (38)$$

$$P(z,0) = P_{out};\ T(z,0) = T_{in} \quad (39)$$

The calculations were carried out with the following parameters: a layer height is 20 mm, an average particle size is 1 mm, porosity is 0.4, the initial temperature of the powder is 190 K, and the outer temperature is 473 K. The heat transfer coefficient of the layer surface is 10 W/m^2/K. The effective coefficient of thermal conductivity of powder was calculated according to the recommendations [50]. Hydrate and ice phases have a thermal conductivity of about 0.2-0.5 W/m/K but heating of the whole layer occurs through porous space filled with gas and contact areas between particles, i.e. Biot number for a single particle is still small but Biot number for a layer of particles could be very large.

A numerical algorithm used for the calculations was previously developed for a mathematical model of pyrolysis of woody fuel particles [58]. Each moment is divided into several calculation stages. First, a kinetic step is made, gas sources and heat sinks are calculated. In the next step, the pressure and velocity fields are calculated. Finally, the problem of thermal conductivity is solved. The calculation results are shown in Figs. 14 and 15. It is possible to averagely divide the layer height into sections corresponding to particles and construct the dynamics of heating and dissociation of particles in these sections. Since the layer height is 20 particle diameters, the curves are plotted for these sections with reference to the layer (particle) number, and the calculation is carried out starting from the bottom of the tank.

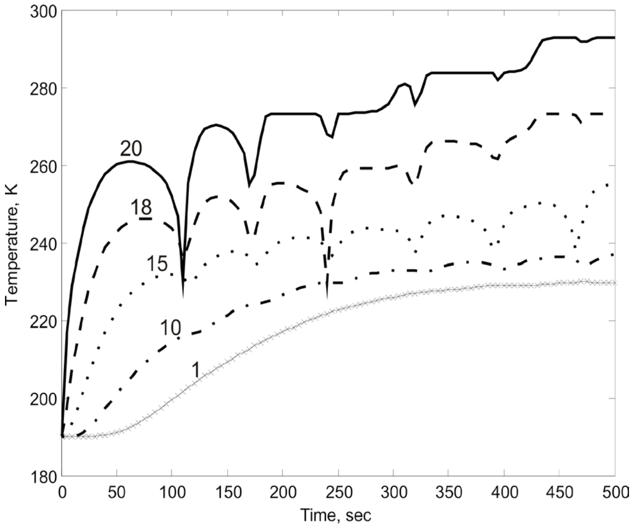

Fig. 14. Dynamics of temperature changes in a layer of gas hydrate particles.

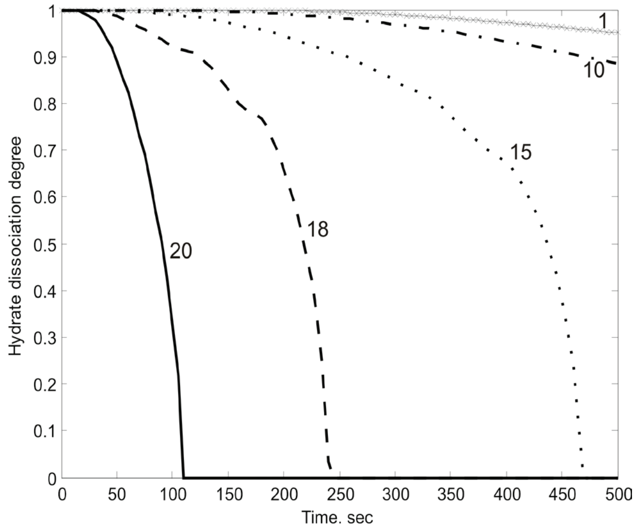

Fig. 15. Dynamics of unreacted hydrate fraction changes in a layer of powder.

To simulate the heating of a layer from the air, it is necessary to take into account the melting of ice at temperatures above 273 K. Therefore, in addition to the equations of thermal conductivity and filtration, the Stefan condition for the phase transition is included in the system. Considering the scheme of layer dissociation similar to that used in [79], we can neglect the effect of water drainage.

Ice melting occurs as a monotonic process of heat absorption at a constant temperature: one can see in Fig. 14 the areas, where the temperature remains constant for long periods. In contrast to melting, dissociation is characterized by significant temperature fluctuations, including those associated with collective effects. Dissociation begins when thermobaric stability limits are reached but it is kinetically limited at low temperatures. Therefore, the heating of the lower layers is faster than the complete dissociation of the upper layers. When dissociation in the 18th particle begins, the surface still does not have time to decompose completely (see Fig. 15). As a result, heat sink intensifies, and sharp minima are observed on the temperature curves. Even the melting of ice on the surface (time point of about 250 s) is interrupted due to the intense absorption of heat by dissociating inner layers. The developed mathematical model will allow us to calculate the variance in the particle decomposition rate in different sections of the layer, find reasonable averaging methods, and compare them with the ones used above.

VII. Conclusions

1. The paper proposes a mathematical model for the dissociation of gas hydrates, which is based on the hypothesis of a filtration mechanism of self-preservation. The model takes into account the kinetics of heterogeneous decomposition and gas transport in the pores of a particle. The presented model is shown to distinguish several conditions of decomposition of hydrate particles. The establishment of these conditions depends on the characteristics of the porous structure of the ice crust. With a high pore density, a kinetic decomposition occurs, and at a low pore density, filtration is involved. For intermediate values of pore density during the decomposition process, the conditions change.
2. Based on the experimental data analysis conducted by different scientific teams, new kinetic coefficients of dissociation of methane hydrate at low temperatures were obtained. The activation energy of the process of low-temperature dissociation (34 kJ/mol) is much lower than the known activation energy of dissociation at temperatures above ice melting, which may be due to a change in the dissociation mechanism.
3. The developed model and new kinetic coefficients were used to reproduce the experimental kinetic features of the methane hydrate dissociation in a thin powder layer: the dependence of the dissociation kinetics on time, particle size, and heat fluxes.
4. A one-dimensional unsteady mathematical model of dissociation of a layer of gas hydrate particles was developed taking into account heat transfer and filtration in a porous volume. The model allows us to investigate the features of the collective behavior of gas-emitting particles, the absorption of dissociation heat, and to evaluate inhomogeneities along the layer height.

Acknowledgments

The theoretical calculations were carried out within the framework of the Melentiev Energy Systems Institute SB RAS Basic Research Program (project No. II.17.1.2, reg. No. AAAA-A17-117030310448-0). The experimental studies were carried out within the framework of the state assignment for the Kutateladze Institute of Thermophysics SB RAS (Project No. AAAA-A17-117080810004-8).

References

[1] E.D. Sloan and C.A. Koh, Clathrate hydrates of natural gases (3rd ed.). Boca Raton, USA: CRC Press, Taylor and Francis Group, 2008.

[2] E.A. Bondarev, V.I. Vasilyev, A.F. Voevodin, N.N. Pavlov and A.P.Shadrina, Thermohydrodynamics of gas mining and transport systems. Novosibirsk: Nauka, 1988. (in Russ.)

[3] Yu.F. Makogon, Hydrates of hydrocarbons. Tulsa, Oklahoma: Pennwell Books, 1997.

[4] N.G. Musakaev, R.R. Urazov, and V.Sh. Shagapov, "Hydrate formation kinetics in piped natural-gas flows, "Thermophys. Aeromech., vol. 13, no. 2, pp. 275-281, 2006. DOI: 10.1134/S0869864306020090

[5] A.A. Makarov (ed.), Forecast of the world and Russian energy sector. Energy Research Institute of RAS, Analytical Center of RF Government. Moscow, 2016.

[6] The International Energy Agency World Energy Outlook 2016. IEA Publications, 2016.

[7] Z. Yin and P. Linga, "Methane hydrates: A future clean energy resource," Chinese J. Chem. Eng., vol. 27, no. 9, pp. 2026-2036, 2019. DOI: 10.1016/j.cjche.2019.01.005

[8] Gas hydrates: extraction technologies and development prospects. Analytical Center of RF Government, 2013.

[9] Y. Cui, C. Lu, M. Wu, Y. Peng, Y. Yao and W. Luo, "Review of exploration and production technology of natural gas hydrate," Adv. Geo-Energy Res., vol. 2, no. 1,pp. 53-62, 2018. DOI: 10.26804/ager.2018.01.05

[10] T. Yu, G. Guan, and A. Abudula, "Production performance and numerical investigation of the 2017 offshore methane hydrate production test in the Nankai Trough of Japan," App. Energy, vol. 251, no. 113338, 2019. DOI: 10.1016/j.apenergy.2019.113338

[11] Y. Sun, X. Ma, W. Guo, R. Jia, and B. Li, "Numerical simulation of the short- and long-term production behavior of the first offshore gas hydrate production test in the South China Sea," J. Petr. Sci. Eng., vol. 181, no. 106196, 2019. DOI: 10.1016/j.petrol.2019.106196

[12] Y.F. Makogon, "Natural gas hydrates – A promising source of energy," J. Nat. Gas Sci. Eng. , vol. 2, no. 1, pp. 49-59, 2010. DOI: 10.1016/j.jngse.2009.12.004

[13] Z.R. Chong, S.H.B. Yang, P. Babu, P. Linga, and X.-S. Li, "Review of natural gas hydrates as an energy resource: Prospects and challenges," App. Energy, vol. 162, pp. 1633-1652, 2016. DOI: 10.1016/j.apenergy.2014.12.061

[14] A. Falenty, W.F. Kuhs, M. Glockzin and G. Rehder, "Self-preservation of CH4 hydrates for gas transport technology: pressure-temperature dependence and ice microstructures," Energy Fuels, vol. 28, pp. 6275-6283, 2014. DOI: 10.1021/ef501409g

[15] H.P. Veluswamy, A. Kumar, Y. Seo, J.D. Lee, P. Linga, "A review of solidified natural gas (SNG) technology for gas storage via clathrate hydrates," App. Energy, vol. 216, pp. 262-285, 2018. DOI: 10.1016/j.apenergy.2018.02.059

[16] G. Rehder, R. Eckl, M. Elfgen, A. Falenty, R. Hamann, N. Kahler, W.F. Kuhs, H. Osterkamp and C. Windmeier, "Methane hydrate pellet transport using the self-preservation effect: a techno-economic analysis," Energies, vol. 5, pp. 2499-2523, 2012. DOI: 10.3390/en5072499

[17] C. Xu, X. Li, K. Yan, X. Ruan, Z. Chen and Z. Xia, "Research progress in hydrate-based technologies and processes in China: A review," Chinese J. Chem. Eng., vol. 27, no. 9, pp. 1998-2013, 2019. DOI: 10.1016/j.cjche.2018.12.002

[18] S.Y. Misyura, "The influence of porosity and structural parameters on different kinds of gas hydrate dissociation," Sci. Rep., vol. 6, no. 30324, 2016. DOI: 10.1038/srep30324

[19] V.Sh. Shagapov, M.K. Khasanov, N.G. Musakaev, and N.H. Duong, "Theoretical research of the gas hydrate deposits development using the injection of carbon dioxide," Internat. J. Heat Mass Trans., vol. 107, pp. 347-357, 2017. DOI: 10.1016/j.ijheatmasstransfer.2016.11.034

[20] V.Sh. Shagapov, G.R. Rafikova, and M.K. Khasanov, "The Theory of the Replacement of Methane by Carbon Dioxide in Gas Hydrates," Theor. Found. Chem. Eng., vol. 53, pp. 64-74, 2019. DOI: 10.1134/S0040579518060118

[21] E.D. Sloan, "Fundamental principles and applications of natural gas hydrates," Nature, vol. 426, pp. 353-363, 2003. DOI: 10.1038/nature02135

[22] A.Yu. Manakov, N.V. Penkov, T.V. Rodionova, A.N. Nesterov, and E.E. Fesenko, "Kinetics of formation and dissociation of gas hydrates," Russ. Chem. Rev., vol. 86, p. 845, 2017. DOI: 10.1070/RCR4720

[23] W. Ke, T.M. Svartaas, and D. Chen, "A review of gas hydrate nucleation theories and growth models," Journal of Natural Gas Science and Engineering, vol. 61, pp. 169-196, 2019. DOI: 10.1016/j.jngse.2018.10.021

[24] Z. Yin, Z.R. Chong, H.K. Tan, and P. Linga, "Review of gas hydrate dissociation kinetic models for energy recovery," J. Nat. Gas Sci. Eng., vol. 35B,pp. 1362-1387, 2016. DOI: 10.1016/j.jngse.2016.04.050

[25] S.D. Sleptsov and V.E. Dontsov, "Modelling of decomposition of a single gas hydrate particle in the water behind the shock wavefront," Thermophysics and Aeromechanics, vol. 17, no. 3, pp. 375-381, 2010. DOI: 10.1134/S086986431003008X

[26] S. Takeya, T. Ebunima, T. Uchida, J. Nagao, and H. Narita, "Self-preservation effect and dissociation rates of CH4 hydrate," J. Crystal Growth, vols. 237-239, pp. 379-382, 2002. DOI: 10.1016/S0022-0248(01)01946-7

[27] V.A. Vlasov, "Formation and dissociation of gas hydrate in terms of chemical kinetics," React. Kin. Mech. Cat., vol. 110, no. 1, pp. 5-13, 2013. DOI: 10.1007/s11144-013-0578-x

[28] T. Bar-Kohany and W.A. Sirignano, "Transient combustion of a methane-hydrate sphere," Comb. Flame, vol. 163, pp. 284-300, 2016. DOI: 10.1016/j.combustflame.2015.10.004

[29] H. Liang, Y. Song and Y. Chen, “Numerical simulation for laboratory-scale methane hydrate dissociation by depressurization,” Energy Conv. Manag., vol. 51, pp. 1883-1890, 2010. DOI: 10.1016/j.enconman.2010.02.018

[30] M. Clarke and P.R. Bishnoi, “Determination of the activation energy and intrinsic rate constant of methane gas hydrate decomposition,” Can. J. Chem. Eng., vol. 79, pp. 143-147, 2001. DOI: 10.1002/cjce.5450790122

[31] S.A. Bagherzadeh, S. Alavi, J.A. Ripmeester, and P. Englezos, “Evolution of methane during gas hydrate dissociation,” Fluid Phase Equil., vol. 358, pp. 114-120, 2013. DOI: 10.1016/j.fluid.2013.08.017

[32] R.V. Belosludov, Y.Y. Bozhko, R.K. Zhdanov, O.S. Subbotin, Y. Kawazoe and V.R. Belosludov, “Hydrogen hydrates: Equation of state and self-preservation effect,” Fluid Phase Equil., vol. 413, pp. 220-228, 2016. DOI: 10.1016/j.fluid.2015.11.031

[33] J. Kondori, S. Zendehboudi, and L. James, “New insights into methane hydrate dissociation: Utilization of molecular dynamics strategy,” Fuel, vol. 249, pp. 264-276, 2019. DOI: 10.1016/j.fuel.2019.02.125

[34] C. Windmeier and L.R. Oellrich, “Visual observation of the methane hydrate formation and dissociation process,” Chem. Eng. Sci., vol. 109, pp. 75-81, 2014. DOI: 10.1016/j.ces.2014.01.018

[35] R.I. Nigmatullin, V.Sh. Shagapov and V.R. Syrtlanov, “Self-similar problem of decomposition of gas hydrates in a porous medium upon depression and heating,” J. App. Mech. Tech. Phys., vol. 39, pp. 421-427, 1998. DOI: 10.1007/BF02468125

[36] M.J. Castaldi, Y. Zhou and T.M. Yegulalp, “Down-hole combustion method for gas production from methane hydrates,” J. Petr. Sci. Eng., vol. 56, pp. 176-185, 2007. DOI: 10.1016/j.petrol.2006.03.031

[37] Y. Liu, Y. Chen, Y. Bai and S. Li, “Similarity theory for the physical simulation of natural gas hydrate reservoir development,” Mining Sci. Tech., vol. 20, pp. 782-788, 2010. DOI: 10.1016/S1674-5264(09)60281-7

[38] Y. Liu and I.K. Gamwo, “Comparison between equilibrium and kinetic models for methane hydrate dissociation,” Chem. Eng. Sci., vol. 69, pp. 193-200, 2012. DOI: 10.1016/j.ces.2011.10.020

[39] E.W. Thiele, “Relation between Catalytic Activity and Size of Particle,” Ind. Eng. Chem., vol. 31, no. 7, pp. 916-920, 1939. DOI: 10.1021/ie50355a027

[40] Ya.B. Zeldovich, Selected works. Volume I: Chemical Physics and Hydrodynamics. Princeton, New Jersey: Princeton Univ. Press, 1992.

[41] M.G. Slin'ko, V.A. Kirillov, I.A. Mikhailova, and S.I. Fadeev, “Mathematical Model of a Catalytic Process on a Porous Grain in a Gas-Liquid–Solid Three-Phase System,” Dokl. Chem., vol 376, pp. 42-45, 2001. DOI: 10.1023/A:1018816527288

[42] O. Senneca, P. Bareschino. M. Urciuolo and R. Chirone, “Prediction of structure evolution and fragmentation phenomena during combustion of coal: Effects of heating rate,” Fuel Proc. Tech., vol. 166, pp. 228-236, 2017. DOI: 10.1016/j.fuproc.2017.06.010

[43] S.L. Singer and A.F. Ghoniem, “Comprehensive gasification modeling of char particles with multi-modal pore structures,” Comb. Flame, vol. 160, pp. 120-137, 2013. DOI: 10.1016/j.combustflame.2012.09.007

[44] E. Chuvilin and B. Bukhanov, “Thermal Conductivity of Frozen Sediments Containing Self-Preserved Pore Gas Hydrates at Atmospheric Pressure: An Experimental Study,” Geosciences, vol. 9, no. 65, 2019. DOI: 10.3390/geosciences9020065

[45] Y.P. Handa, “Compositions, enthalpies of dissociation, and heat capacities in the range 85 to 270 K for clathrate hydrates of methane, ethane, and propane, and enthalpy of dissociation of isobutane hydrate, as determined by a heat-flow calorimeter,” J. Chem. Thermodynamics, vol. 18, pp. 915-921, 1996. DOI: 10.1016/0021-9614(86)90149-7

[46] S.A. Aromada, B. Kvamme, N. Wei, and N. Saeidi, “Enthalpies of Hydrate Formation and Dissociation from Residual Thermodynamics,” Energies, vol. 12, no. 4726, 2019. DOI: 10.3390/en12244726

[47] A.H.S. Dehaghani and B. Karami, “A new predictive thermodynamic framework for phase behavior of gas hydrate,” Fuel, vol. 216, pp. 796-809, 2018. DOI: 10.1016/j.fuel.2017.11.128

[48] D.B. Spalding, Combustion and mass transfer. Oxford: Pergamon Press, 1979.

[49] V.A. Vlasov, “Diffusion model of gas hydrate dissociation into ice and gas: Simulation of the self-preservation effect,” Internat. J. Heat Mass Trans., vol. 102, pp. 631-636, 2016. DOI: 10.1016/j.ijheatmasstransfer.2016.06.057

[50] M.E.Aerov, O.M.Todes, and D.A.Narinskii, Stationary granular beds: hydraulics and heat transfer. Leningrad: Khimiya, 1979. (in Russ.)

[51] A. Fujimoto and T. Sugahara, “Scanning electron microscopic studies on the methane hydrate decomposition using the freeze-fracture replica method,” Bull. Glaciolog. Res., vol. 35, pp. 39-45, 2017. DOI: 10.5331/bgr.17R02

[52] H.C. Kim, P.R. Bishnoi, R.A. Heidemann, and S.S.H. Rizvi, “Kinetics of methane hydrate decomposition,” Chem. Eng. Sci., vol. 42, no. 7, pp. 1645-1653, 1987. DOI: 10.1016/0009-2509(87)80169-0

[53] S. Takeya, T. Uchida, J. Nagao, R. Ohmura, W. Shimada, Y. Kamata, T. Ebunima, and H. Narita, "Particle size effect of CH4 hydrate for self-preservation, ”Chem. Eng. Sci., vol. 60, no. 5, pp. 1383-1387, 2005. DOI: 10.1016/j.ces.2004.10.011

[54] L.A. Stern, S. Circone, S.H. Kirby and W.B. Durham, “Anomalous preservation of pure methane hydrate at 1 atm,” J. Phys. Chem. B, vol. 105, pp. 1756-1762, 2001. DOI: 10.1021/jp003061s

[55] S.Ya. Misyura, “Effect of heat transfer on the kinetics of methane hydrate dissociation, ”Chem. Phys. Lett., vol. 583, pp. 34-37, 2013. DOI: 10.1016/j.cplett.2013.08.010

[56] E. Chuvilin, B. Buhanov, O. Guryaeva, V. Istomin, S. Takeya, and A. Hachikubo, “Experimental study of self-preservation mechanisms during gas hydrate decomposition in frozen sediments,” Proc. 7th Internat. Conf. Gas Hydrate (ICGH 2011). Edinburgh, Scotland, UK, July 17-21 2011.

[57] E. Ranzi, M. Corbetta, F. Manenti and S. Pierucci, “Kinetic modeling of the thermal degradation and combustion of biomass,” Chem. Eng. Sci., vol. 110, pp. 2-12, 2014. DOI: 10.1016/j.ces.2013.08.014

[58] I.G. Donskoy, “Mathematical modeling of woody particles pyrolysis in a fixed bed, ” Computational Technologies, vol. 23, no 6, pp. 14-24, 2018. DOI: 10.25743/ICT.2018.23.6.003 (in Russ.)

[59] S.Y. Misyura and V.S. Morozov, “Influence of the granule size and composition uniformity on methane hydrate dissociation,” J. Phys. Conf. Ser., vol. 1128, no. 012072, 2018. DOI: 10.1088/1742-6596/1128/1/012072

[60] V.P. Mel'nikov, A.N. Nesterov and A.M. Reshetnikov, “Formation of supercooled water upon dissociation of propane hydrates at T < 270 K,” Dokl. Phys. Chem., vol. 417, pp. 304-307, 2007. DOI: 10.1134/S0012501607110048

[61] V.P. Mel'nikov, A.N. Nesterov, L.S. Podenko, A.M. Reshetnikov, and V.V. Shalamov, “Metastable states of gas hydrates under pressures lower than equilibrium pressures of the ice-hydrate-gas system,” KriosferaZemli, vol. 15, no. 5, pp. 80-83, 2011. (in Russ.)

[62] A. Falenty and W.F. Kuhs, “Self-preservation of CO2 gas hydrates - surface microstructure and ice perfection,” J. Phys. Chem. B, vol. 113, pp. 15975-15988, 2009. DOI: 10.1021/jp906859a

[63] O.S. Subbotin, V.R. Belosludov, T. Ikeshoji, E.N. Brodskaya, E.M. Piotrovskaya, V. Sizov, R.V. Belosludov, and Y. Kawazoe, “Modeling the Self-Preservation Effect in Gas Hydrate/Ice Systems,” Mat. Trans., vol. 48, no. 8, pp. 2114-2118, 2007. DOI: 10.2320/matertrans.N-MRA2007866

[64] V.R.Belosludov, Y.Y.Bozhko, and R.K. Zhdanov, “Self-preservation effect modeling in hydrate systems using Lattice Dynamic methods,” J. Phys.: Conf. Ser., vol. 1128, no. 012086, 2018. DOI: 10.1088/1742-6596/1128/1/012086

[65] V.A. Vlasov, “Phenomenological diffusion theory of the formation of gas hydrate from ice powder,” Theor. Found. Chem. Eng., vol. 46, pp. 576-582, 2012. DOI: 10.1134/S0040579512060243

[66] A.A. Sizikov, V.A. Vlasov, A.S. Stoporev, A.Y. Manakov, "Decomposition Kinetics and Self-Preservation of Methane Hydrate Particles in Crude Oil Dispersions: Experiments and Theory," Energy Fuels, vol. 33, no. 12, pp. 12353-12365, 2019. DOI: 10.1021/acs.energyfuels.9b03391

[67] V.A. Vlasov, “Mathematical Model of the Effect of Self-Preservation of Gas Hydrates,” J. Eng. Phys. Thermophys., vol. 92, no. 6, pp. 1406-1414, 2019. DOI: 10.1007/s10891-019-02057-8

[68] V.A. Vlasov, “Diffusion model of gas hydrate dissociation into ice and gas that takes into account the ice microstructure,” Chem. Eng. Sci., vol. 215, no. 115443, 2020. DOI: 10.1016/j.ces.2019.115443

[69] W. Liu, Q. Li, Y. Song, L. Zhang, M. Yang, L. Wang, and Y. Chen, “Diffusion Theory of Formation of Gas Hydrate from Ice Powder without Melting,” Energy Procedia, vol. 61, pp. 513-522, 2014. DOI: 10.1016/j.egypro.2014.11.1161

[70] I.G. Donskoy and S.Ya. Misyura, “Dissociation model of gas hydrate particle with consideration of methane filtration in the pores of ice crust,” Modern Science. Researches, Ideas, Results, Technologies, no. 1 (16), pp. 241-245, 2015.

[71] S.Y. Misyura and I.G. Donskoy, “Dissociation of natural and artificial gas hydrate,” Chem. Eng. Sci., vol. 148, pp. 65-77, 2016. DOI: 10.1016/j.ces.2016.03.021

[72] G.R. Galavas, “A random capillary model with application to char gasification at chemically controlled rates,” AIChE J., vol. 26, no. 4, pp. 577-585, 1980. DOI: 10.1002/aic.690260408

[73] S.K. Bhatia and D.D. Perlmutter, “A random pore model for fluid-solid reactions: II. Diffusional and transport effects,” AIChE J., vol. 27, no. 2, pp. 247-254, 1981. DOI: 10.1002/aic.690270211

[74] I.G. Donskoi, “Process simulation of the co-gasification of wood and polymeric materials in a fixed bed,” Solid Fuel Chem., vol. 52, no. 2, pp. 121-127, 2018. DOI: 10.3103/S0361521918020027

[75] I.G. Donskoy, “Mathematical modeling of the agglomeration in a reactive porous medium with variable permeability,” Computational Technologies, vol. 25, no. 2, 2020. DOI: 10.25743/ICT.2020.25.2.003 (in Russ.)

[76] S.Y. Misyura, “Dissociation of natural and artificial methane hydrate,” EPJ Web of Conf., vol. 110, no. 01040, 2016. DOI: 10.1051/201611001040

[77] G. Cui, S. Wang, Z. Dong, X. Xing, T. Shan, and Z. Li, “Effects of the diameter and the initial center temperature on the combustion characteristics of methane hydrate spheres,” App. Energy, vol. 257, no. 114058, 2020. DOI: 10.1016/j.apenergy.2019.114058

[78] S.Y. Misyura, “Non-stationary combustion of natural and artificial methane hydrate at heterogeneous dissociation,” Energy, vol. 181, pp. 589-602, 2019. DOI: 10.1016/j.energy.2019.05.177

[79] F.H. Wu, R.E. Padilla, D. Dunn-Rankin, G.B. Chen, and Y.C. Chao, “Thermal structure of methane hydrate fueled flames,” Proc. Comb. Inst., vol. 36, no. 3, pp. 4391-4398, 2017. DOI: 10.1016/j.proci.2016.06.012

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Prospects for the development of Mongolia's Coal export

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***Abstract* — In recent years, Mongolian coal export has grown and gained great importance for the country. The significant resources of high-quality coal and demand for coal in the international market contribute to the augmentation of Mongolian coal export. The expanding coal supplies to the international market affect greatly the development of coal mining in Mongolia. The paper presents the status of coal resources and the characteristics of the most ambitious projects for the development of coal export. The most significant coal development projects are mainly related to the development of deposits in the South Gobi region. Foreign companies that hold licenses for the development of deposits take part in the development of coal deposits. Current and potential future restrictions on the development of coal export are given. The main of them are the lack of access to the seacoast, as Mongolia is a landlocked country; state of transportation infrastructure; the availability of resources for the development of production, and the geopolitical conditions affecting the demand for coal in the world market. Coal exports can be delivered to the international market from the seaports of China and Russia, through the territories of these countries. Further increase in coal export from Mongolia depends on the development of transportation and production infrastructures; the situation in the international coal market; the availability of resources for the development of deposits; and opportunities to increase the volume of exploration. In the future, Mongolia could become one of the world's major coal exporters.**

***Index Terms* — Mongolia, coal, reserves, mining, projects, export, coal transportation.**

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http://dx.doi.org/10.38028/esr.2020.01.0004
Received April 06, 2020. Revised May 10, 2020.
Accepted May 27, 2020. Available online July 31, 2020.

I. Introduction.

The export of goods is of great importance for the economy of Mongolia. Fossil resources such as gold, coal, copper concentrate, zinc and iron ores, and crude oil account for more than 80% of exports [1,2]. Coal export is developing at the fastest pace and in recent years it has surpassed the export of other goods. The significant resources of high-quality coal [3, 4] and the growing demand for Mongolian coal in the international market create the prospects for increasing coal exports from Mongolia. According to international statistics [5], since 2016 Mongolia has been among the top ten countries in terms of coal export and in terms of export-to-production ratio. Mongolia is second only to Australia in per capita coal production. In 2016, Mongolia ranked 21st in coal production among the countries mining coal, and in 2018, it ranked 14th [6].

Currently, the main importer of Mongolian coal is China, the world's largest importer of coal. In 2018, small shipments of coal were delivered to Hong Kong and Great Britain. In 2018, coal exports accounted for 62% of the total coal production [2]. In 2015-2018, revenues from coal export increased by more than 100 times and amounted to about $ 2,800 million in 2018.

The main export markets for Mongolian coal intersect with the Russian ones. This is, first of all, China, importing both Russian and Mongolian coal. Japan, Korea, and other countries of Northeast Asia (NEA), importing Russian coal, are potential importers of Mongolian coal.

II. A retrospect of coal industry development

The dynamics of coal production and supply development is shown in Figure 1. The main increase in production is due to rising demand for coal in the international coal market, against the background of a stable, although an insignificant, increase in supplies for domestic consumption.

From 2005 to 2018, coal production increased almost by 7 times from 7.5 million tons to 51.4 million tons, while coal export rose by more than 15 times from 2.1 million tons to 32 million tons, and the supplies to the domestic market increased only by 1.7 times from 5.5 million tons to 9.5 million tons [2, 7].

The most important type of fuel in the domestic market

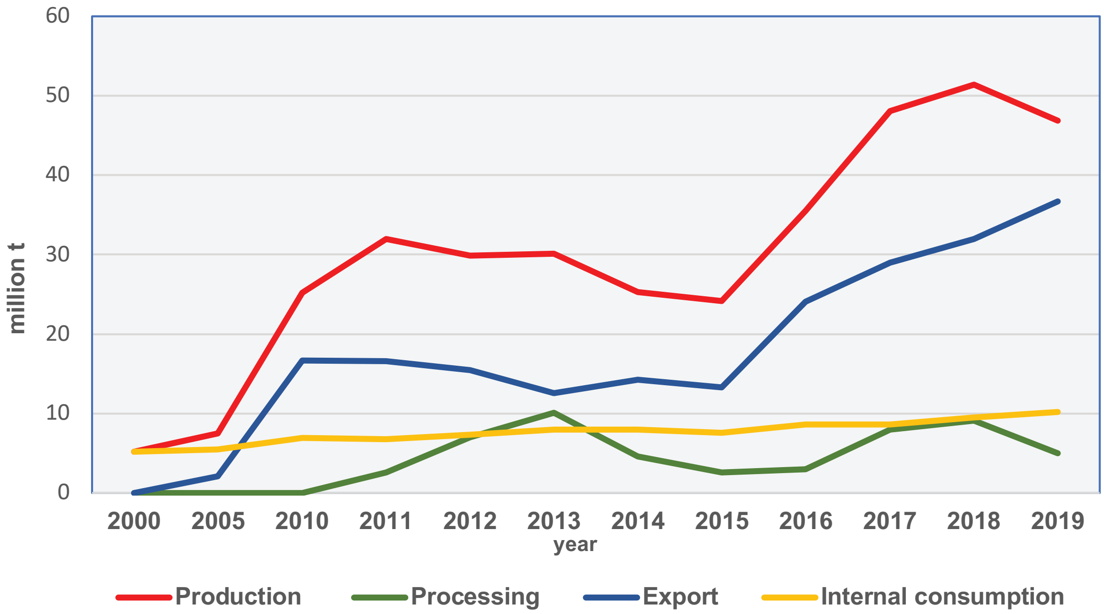

Fig. 1. – Indices of coal production and supplies. Source: [2].

in Mongolia is coal [8.9]. Coal reserves significantly exceed those of oil and gas. The share of coal in the consumption of primary energy resources in retrospect ranged from 60 to 80% [10]. The main consumers of coal in Mongolia are power plants. Coal consumption by power plants accounts for about 80% of the total coal supplies to the domestic market.

Coal is mined by both state and private enterprises. Coal mining by state-owned enterprises increased by more than three times in 2005 - 2018 (from 4.5 to 16.5 million tons), and the amount of coal mined by private enterprises rose by more than 10 times (from 3, 1 to 34.9 million tons). The share of exports in deliveries also increased from 28% in 2005 to 77% in 2018. Coal is exported mainly by private companies. Mainly coking coal is exported, both washed and unwashed. The share of coking coal in export deliveries is about 70%. The supply of Mongolian coal to China is gradually replacing coal supplies from Russia, Canada, Australia, and the United States. The price of Mongolian coal on the border with China in January 2018 was $ 65.5 - 70.5 per ton, which allows Mongolia to compete with coal exporters to NEA countries, i.e. Russia, Australia, Indonesia, Canada, and others. [11].

III. Coal resources for export

The coal resources of Mongolia are estimated at 173.5 billion tons, and the explored reserves of the A + B + C1 categories are 33.1 billion tons as of 1.01.2020 [5, 7]. There are deposits and manifestations of coal in almost all areas of the country. The ratio of reserves to resources for different coal basins ranges from 0 to 30%, on average - 18%, which indicates a low degree of exploration of deposits. Of the 15 coal basins, the most studied ones are the South Gobi (hard coal) and Choyr-Nyalga (brown coal). For the development of coal export, the most attractive deposits are the deposits of coking and high-quality steam coal, mainly in two areas: the southern (South Gobi and South Hangai basins) and central (Choyr-Nyalga basin). The southern area is characterized by a semi-desert climate, lack of water supply, high-quality coal, and a small-scale of coal mining for local needs. Most of the coal mined in the area is exported. The central area is characterized by

Table 1. Coal mining development projects for coal export

Deposit	Coal reserves, million t	Thickness of seams, m	Potential production, million t	Year of commissioning	Volume of production in 2019, million t	The state of the infrastructure at the beginning of the project: the road to the nearest border crossing; power source
Tavan Tolgoi	1600	2 – 86,2	15-20	1966*, 2010/ 2013	16,5	254 km; central grid and diesel power plants
Ukhaan Khudag	505	30-60	15	2009	10,0	245 km; central electric grid and power plant with a capacity of 18 MW.
Ovoot Tolgoi	302	35	9	2008	5,0	44.8 km; electric grid of China and diesel generator
Nariin Sukhait	587.5	53,8	14	2008	3,6	44.8 km; electric grid of China
Khoshoot	300	40,0	3	2011	3,6	310 km; diesel power plant

* western section with reserves of 218.7 million t. Source: [12-15].

stable mining and geological conditions, and large-scale coal mining for domestic consumption.

Most deposits are suitable for open-pit mining. The depth of bedding is from 200 to 500 m, and only for the Tavan Tolgoi deposit, it is up to 1000 m, and the thickness of seams varies from 2 to 100 m. Coals of the largest deposits are characterized by high quality, medium ash content (8.7-20.9%), low sulfur content (0.3-0.8%), and a sufficiently high calorific value [9]. The main projects for increasing coal exports are presented in the 2016 annual report of the Ministry of Mining of Mongolia [12]. Table 2 shows the projects for which the coal reserves of the developed deposits exceed 100 million tons. The presented deposits are situated in the south of Mongolia (the Khoshoot deposit is in the coal basin of South Khangai, and the rest of the deposits are in the coal basin of the South Gobi). The deposits have reserves of coking and high-quality steam coal. Mining and geological conditions for the development of deposits are mostly favorable. The deposits are suitable for open-pit mining. There are coal processing facilities at the Ukhaa Khudag and Khoshoot deposits. Transportation infrastructure is poorly developed. The operating life of the Tavan-Tolgoi deposits is more than 200 years, and that of the rest of the deposits is 40-50 years in terms of 2018 production levels.

Multinational companies from leading developed countries, which are deficient in coking coals, show an increased interest in promising deposits, primarily China. The licenses for the development of the presented coal deposits are partially or fully owned by foreign companies; international organizations take part in funding the projects. Mongolian companies are also involved in the development of the deposits.

The most significant projects are the development of Ovoot Tolgoi and Tavan Tolgoi deposits. Tavan Tolgoi is the world's largest and most promising deposit.

The Ovoot Tolgoi high-quality coking coal deposit is located at a distance of 46 km from the border with China. About 90% of coal reserves are suitable for open-pit mining. SouthGobi Resources Ltd., a Canadian company, has a license to develop more than 80% of the deposit.

The Tavan Tolgoi deposit is located in the South Gobi region, at an altitude of 1500-1830 meters above sea level, at a distance of 50-270 km from the border with China. The deposit has the reserves of high-quality coking and steam coal, including scarce grades (K, KZh, Zh). The project suggests the construction of processing plants, a coal-fired power plant, and a 70 km pipeline for water supply. In the future, production and processing at two coal washing plants may amount to 30 million tons per year. Mining has been performed at the site of the Western Tsanghi deposit since 1967. The coal mined was supplied to the domestic market of Mongolia. Erdenes TavanTolgoi (ETT), a Ulan Bator company, currently holds the licenses for the deposit development. Apart from the deposit development, foreign companies are planning to build a 400-kilometer railway line from Tavan Tolgoi to the city of Sai-shand adjacent to the existing Ulan-Bator railway network (UBRN), modernize it and use the port facilities of Siberian Coal Energy Company in the Far East.

Fig. 2. Potential transportation corridors to seaports. Source: [1].

In addition to the projects presented, there are also smaller-scale projects and projects for the development of steam coal deposits, both for domestic consumption and for export. Implementation of the projects involves building transportation infrastructure and supplying electricity, water, and other resources. The timing of project implementation depends on the implementation of these activities, the availability of investments, and the situation in the global coal market.

IV. Possible restrictions on the development of coal exports from Mongolia

In addition to favorable conditions for the development of Mongolian coal export such as the available reserves of high-quality coal, which is in demand at the international market, there are also certain restrictions. The main restrictions are connected with the lack of access to the seacoast, poor development of internal transportation infrastructure, the availability of resources for the development of deposits, geopolitical, and other conditions.

1. Lack of access to the seacoast

Mongolia is a landlocked country that does not have access to the seacoast. It borders two giant neighbors Russia and China. Currently, about 99% of coal is exported to China.

There are two possible directions of deliveries to the international market: either through the territory of China or through the territory of Russia to seaports. Multilateral cooperation with Russia and China is necessary, to provide transit traffic through the territories of these states to seaports. This creates Mongolia's dependence on the policies of Russia and China, through which Mongolian coal can be delivered to the international market. Possible transportation corridors are to the border with Russia or China and further along the territory of Russia to the far-eastern ports, or through China to the nearest ports (Fig. 1) [1, 16].

The most promising coal deposits suitable for export are located in the south of Mongolia, quite close to the Chinese border. The distance from coal mining enterprises on paved roads to the major crossings on the border with China ranges from 45 to 310 km [9]. From a logistics point of view, it would be most rational to supply coal to NEA markets through China. China has high-capacity port coal terminals Qinhuangdao (cargo turnover of 226.4 million tons/year) and Tianjin (100 million tons/year) - according to SCEC and the Coal Industrial Company [18]. The difficulties for the development of this supply chain are due to the interest of Chinese entrepreneurs in buying coal at low prices on the Mongolian border and then reselling it to the international market.

The transportation of Mongolian coal through the territory of Russia is complicated by competition between Mongolian and Russian coal mining companies that supply coal to the countries of NEA. Russian ports largely control coal companies that supply coal to potential importers of Mongolian coal. There are also restrictions on the throughput capacity of Russian railways and the capacity of Russian coal terminals in shipping ports in eastern Russia (less than 25 million tons/year for each of the coal terminals in the Vostochny and Vanino ports, which in total is almost by 7 times less than the Chinese terminals). It is planned to modernize the capacities of coal terminals and build new ones but the increase in the throughput capacity of the Russian railways does not keep pace with the growing demand for transportation of cargos.

A research team of the International Bank for Reconstruction and Development [19] estimated the total costs of coal mining and coal railway transportation. The calculations were performed for various potential rail routes for deliveries of coal from the Tavan-Tolgoi deposit to Russian and Chinese ports, depending on the annual volume of coal production. Seven routes were considered, three to Chinese ports and four to Russian. According to the calculation results, the costs of extraction and transportation to Russian Far-Eastern ports exceed the costs of transportation to Chinese ports by 1.5-2 times. The calculations were made under the assumption that all coal mined is transported by this route, the actual transportation prices can be higher and they can be determined by commercial agreements. A similar analysis was carried out for potential rail routes for coal transportation from Nariin Sukhait.

2. Transportation infrastructure of Mongolia

The transportation infrastructure of Mongolia is characterized by weak spatial and structural ties; significant distances between existing transportation junctions; extreme environmental conditions; poor technical equipment of roads; low density of roads in general and roads with the hard and improved pavement, in particular [20].

The main railway of the country connecting Ulan Bator with Russia and China, and thereby East Asia with Europe, is the Ulan Bator Railway (UBR). It provides domestic and transit transportation of cargos in Mongolia. UBR is of great strategic importance not only for Mongolia but also for the Russian Federation and China. At present, the operational length of the Mongolian railways is more than 1800 km [21]. It accounts for over 80% of all freight and passenger transportation in the country. UBR was built shortly after the end of World War II and now it is operating at the limit of its possibilities. The carrying capacity of the line is 25 million tons per year [22], which is less than the weight of exported goods. The total volume of cargo transported by UBR is constantly growing [2]. In 2018, the volume of traffic on the UBR increased by 8% compared to 2017 and amounted to 24.5 million tons. At the same time, transit and import traffic rose by 27%. By 2030, freight traffic is expected to increase further and reach 50 million tons [23, 24].

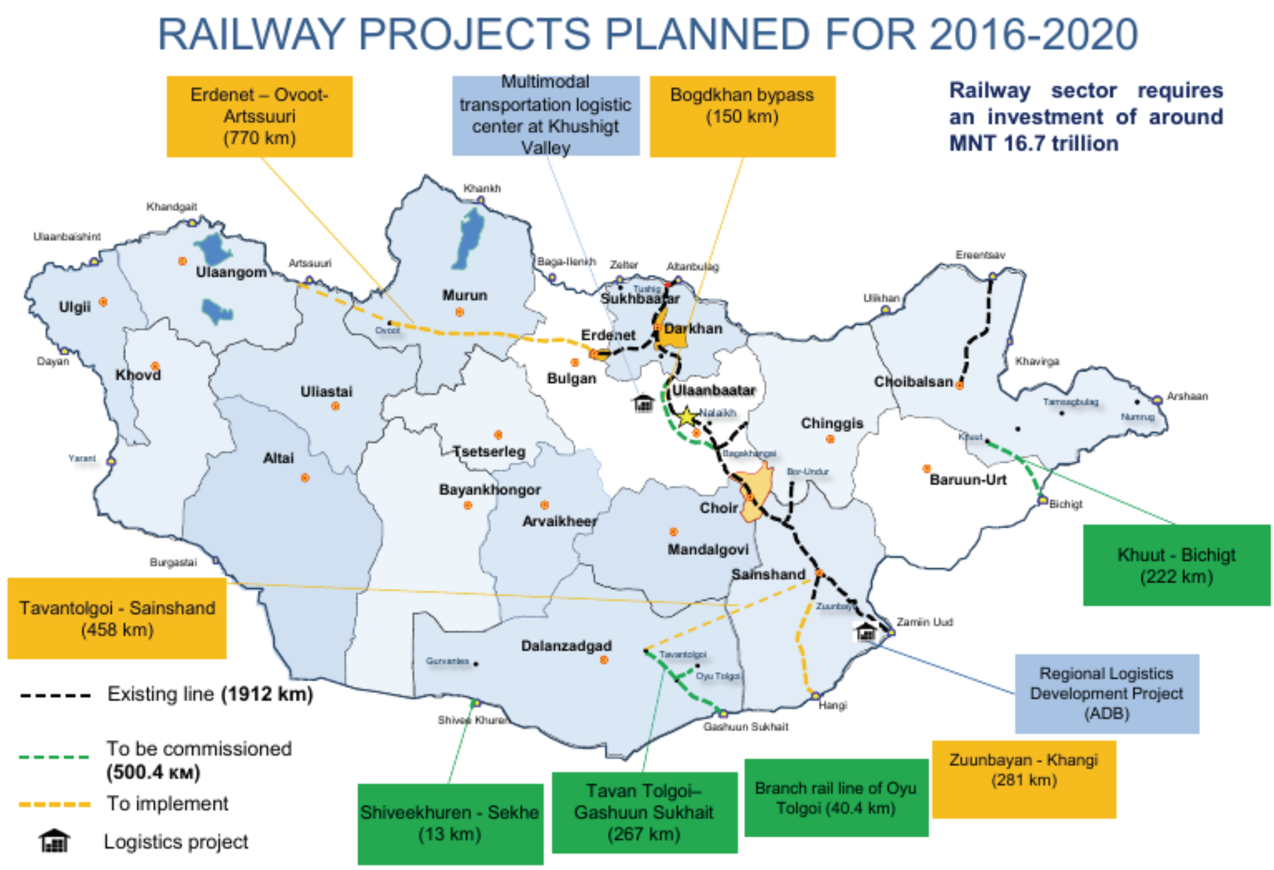

Fig. 3. Projects for the development of railway infrastructure. Source: [16].

Coal for domestic consumption is supplied by rail and road. Most of the coal for export is transported to the Chinese border by truck.

The need for transportation of increasing volumes of cargos creates the need for further development of transportation infrastructure, including UBR, and paved roads. Prospective export-oriented coal deposits do not have access to the main railway line. The development of the coal industry in Mongolia, focused on coal export, requires the development/modernization of existing railways and the construction of new ones. The strategic objectives for the development of Mongolian railways are presented in the document "Concept for the implementation of a joint Russian-Mongolian project for the development of JSC "UBR" and the construction of new railway infrastructure" [25]. The project involves the modernization of the existing network of JSC "UBR", as well as the construction of new railway lines connecting coal deposits and border crossings or/and UBR (Table 3, Fig. 2). The total length of these lines is 2.2 thousand km.

Two railway options are considered to supply coal from the Tavan Tolgoi deposit: to the border crossing on the border with China (Tavan Tolgoi – Gashuun Sukhait) and with access to the main UBR line (Tavan Tolgoi-Zuunbayan). The second option opens the door for transporting Tavan Tolgoi coal both southward to China and northward to Russia and further to the Far-Eastern ports of Russia. The construction of this line is already underway.

Railway lines designed for the Tavan Tolgoi deposit can also serve the coal deposits of Ukhaa Khudag and Nariin Sukhait.

For the Ovoot Tolgoi deposit, located in the northwest of Mongolia, access to international markets is planned through the construction of the Erdenet-Ovoot-Artsuuri railway. The section of the future railway will have access to the Russian border in northern Mongolia and the UBR.

The study of the International Bank for Reconstruction and Development [19] gives the feasibility criteria for the construction of railway lines for coal export and their approximate cost. The construction of one kilometer of the railways is estimated at $ 1.8 million and it will be economically viable only for the transportation volumes of at least 2-4 million tons per year. Most coal mining development projects meet this criterion.

International companies from Canada, Japan, China, and Russia (JSC "Russian Railways") participate in the development and implementation of the projects for building the transportation infrastructure in Mongolia to export coal. This, in addition to the construction and reconstruction of railways and dirt roads, entails the expansion of the throughput potential of border ports and transshipment points, the construction of a basic track structure, residential buildings, and administration buildings at some railway junctions.

Table 2. Projects for construction of new railway lines. Source: [16].

Project	Distance, km	Project status
Erdenet –Ovoot –Artsuuri	770	At the design stage
Tavan Tolgoi-Zuunbayan (Sainshand)	458	Construction started in May 2019
Zuunbayan Khangi	281	Feasibility study is developed
Tavan Tolgoi – Gashuun Sukhait	267	Construction work is in progress
Khoot Bichigt	222	Feasibility study is approved, engineering design is made
Bogdhan Bypass	150	Feasibility study is developed
Oyu Railway	40,4	Engineering design is made
Shiveekhuren-Sekhe	13	Engineering design is under development (the railway gauge is negotiated)

3. Resources for the development of deposits

The development of coal mining is associated with the attraction of labor resources to the settlements closest to the mines. This also includes providing workers and their families with housing and related infrastructure. According to the estimates of the International Bank for Reconstruction and Development, the expansion of coal production at export-oriented coal deposits will require additional 80 thousand people, including about 17 thousand people for the Tavan Tolgoi and 33.5 thousand people for the Oyu Tolgoi. The amount of necessary investment in housing and infrastructure is estimated at $ 1.4 billion. These data are already somewhat outdated but give an idea of the necessary resources.

The electricity and water supply to coal-mining enterprises and related settlements is very important. Most prospective deposits are located in the South Gobi region, which is scarce in water resources.

As for the electricity supply, the projects for the development of the deposits suggest providing electricity either through the construction of power plants on the coal of the deposit, or the reconstruction and expansion of the capacity of power plants operating in the settlements closest to the deposits under development, or through the export of electricity from China. The largest power plants are planned to be built at the Shivee Ovoo deposits, with a capacity of 5250 MW and at the Tavan-Tolgoi deposit with a capacity of 600 MW. A coal-fired power plant at the Shivee Ovoo deposit is planned as part of the China-Mongolia-Russia Economic Corridor project, with the prospect of electric power transmission to the PRC.

Initially, a diesel generator was used at the Tavan Tolgoi deposit. The commissioning of a 600 MW power plant will ensure all types of activities in the Eastern and Western sections of the Tavan Tolgoi deposit, including a washing plant, and a system of water supply to the population and to the mines in the South Gobi region. The expected surplus power is planned to be transferred to the Mongolian network or China. Commissioning of the power plant is planned for 2023. The cost of the construction of the 600 MW power plant is estimated at $ 0.5 billion [26].

4. Geopolitical and other conditions

According to forecasts made by international organizations, the prospects for coal consumption in the world are ambiguous and highly uncertain [27-30]. This is associated with the environment and climate policy of the countries, which is focused on measures intended to ensure low-carbon development, and as a result, to reduce coal consumption. Coal consumption is also affected by the possible slowdown or acceleration of economic growth in importing countries, primarily in China. According to the World Bank and the Russian Academy of Sciences, the Asian region consumes 75.7 percent of the world's coal, including 66 percent of it in China and India. (Source: World Bank, News of the Russian Academy of Sciences). NEA countries are potential importers of Mongolian coal. However, China remains the main importer of Mongolian coal. Growth in demand for imported coal is projected only in some NEA countries with a decrease in demand in China, the world's largest producer and consumer of coal. The demand for coal is projected to stabilize in South Korea, Japan, and Taiwan, while its growth is expected in India.

The factors restraining the growth of demand for coal in China are determined by internal policy on energy sources. These are reduction in energy-intensive production, accelerated development of new energy sources and advancements in the field of energy conservation, and unpredictable economic development conditions. As regards China's foreign policy, in retrospect, the growth of coal imports from Mongolia was affected by trade sanctions against North Korea, which were also imposed on coal imports.

The development of coal mining and the transportation system of Mongolia is largely dependent on foreign capital. A possible decrease in the interest of foreign investors caused by anti-investment laws and other factors can significantly affect the growth rate of coal production.

Thus, the development of Mongolian coal export depends not only on the energy prices at the world market but also on domestic and foreign policies of the countries importing coal, primarily China.

Other conditions include increased volumes of exploration, climatic conditions, and unpredictable events in the world.

Since Mongolia's coal reserves are poorly studied, an increase in the volume of exploration will allow identifying other coal deposits or areas of coal deposits that are promising for development.

Climatic conditions are associated with the sharply continental climate of Mongolia: at certain times (mainly in the South Gobi basin), miners deal with temperatures that range from -40°C to +40°C. This can limit some types of work compared to other regions where earthwork can be performed year-round [31].

The unpredictable events in the world, such as the fires in Australia, the epidemic of the coronavirus, the sanctions imposed by individual states, and similar global phenomena can slightly affect the demand for Mongolian coal.

Large-scale forest fires in Australia, which is the world's leading producer of coking coal, can, to some extent, affect the situation in the global market. The coronavirus epidemic caused the introduction of temporary transportation restrictions to stop the spread of the virus, which affects the volume and speed of deliveries.

Conclusion

Mongolia has high-quality coal resources that are in demand at the global coal market. The coal consumption forecast made by international organizations for the potential importers of Mongolian coal is favorable for the intensive development of coal export from Mongolia.

Mongolia can enter the wider international coal market only through the ports of China or Russia. There are restrictions caused not only by the state of the Mongolian transportation infrastructure but also by the throughput capacity of Chinese and Russian railways from the Mongolian border to coal shipping ports and port facilities. Russia and China cannot always offer Mongolia favorable coal transportation conditions. Russian coal companies exporting coal through the ports of the Far East are not interested in the appearance of a competitor in the NEA market, which may affect tariffs in the coal shipping terminals controlled by them.

Prospects for the development of coal export depend on the state of the transportation and production infrastructure; opportunities to increase exploration work; development potential of domestic and foreign coal markets; geopolitical conditions limiting coal consumption; Russia and China's policies on the organization of transportation corridors to seaports to allow Mongolian coal to enter the NEA markets; the availability of investment, including foreign one for the implementation of projects. International companies participate in the development and implementation of projects related to the development of coal deposits and coal supplies for export, which has a positive effect on the development of the coal industry in Mongolia.

The state policy of Mongolia is aimed at supporting the development of the coal industry in various areas, including cooperation with international organizations; attraction of domestic and foreign investors; creation of a free market mechanism – deregulation of coal pricing; training skilled labor, and others.

In this situation, it seems important to direct the joint efforts of Mongolia, Russia, and China to develop measures to ensure the competitiveness of coal through integrated processing.

The capacity of the international coal market for Mongolian coal will remain favorable. Mongolia is already competing with the world's leading coal exporters, so far only with those exporting coal to China. In the future, under favorable conditions, Mongolia may become one of the main coal exporters to the countries of NEA.

The study was funded by the international grant of the Russian Foundation for Basic Research (project No. 18-510-94006) and the Ministry of Education, Culture, Science, and Sport of Mongolia (project No. ShuGh / OKhU / 2018/26)

References

[1] Gotov Dugerjav, Enhancing Northeast Asia and Mongolia Economic Cooperation through Developing Transport Corridors. [Online]. Available: http://www.cscap.org/uploads/docs/Related%20Research/10GenConf/7GotovDugerjav(Mongolia)10GC.pdf)

[2] Mongolian Statistical Information Service www.1212.mn

[3] Vorobiov B.M. Coal of the World / Edited by L.A. Puchkova. - M.: Publishing House "Mountain Book", 2013, v.III; Coal of Eurasia. 752 p.

[4] Plakitkina L.S., Plakitkin Yu.A. The coal industry of the world and Russia: analysis, trends, and development prospects / - M.: Literature, 2017. - 374 p.

[5] Key world energy statistics. IEA 2019 -81 p. [Online]. Available: http://www.iea.org/statistics/

[6] BP Statistical Review of World Energy June 2018 [Online]. Available: https://nangs.org/analytics/bp-statistical-review-of-world-energy

[7] Ochirbat Punsalmaagiin. The coal industry of Mongolia: state and development prospects // Notes of the Mining Institute. 2017.v. 226. pp. 420-427. DOI: 10.25515/PMI.2017.4.420

[8] Status and Challenges to Coal Industry for Sustainable Development in North-East Asia and Identification of Opportunities for Subregional Cooperation in the Coal Sector: Intergovernmental Cooperation in Northeast Asia, Joint Study, Working Group on Coal /Melentiev Energy Systems Institute Of Siberian Branch of Russian Academy of Sciences, Moscow – Irkutsk, 2011. – 146 p.

[9] Mongolian statistical yearbook. Edited by S/ Mendsaikhan, G. Gerelt-Od, B. Erdenesuren, Kr. Bajiikhun, UlaanBaatar, 2015. 413 p.

[10] Yeren-Ulzii, Energy statistics, and trade of Mongolia for 2016 country report, 2016 Joint Study Expert Workshop 13 April 2017, Seoul. -17 p.

[11] UN Comtrade Database [Online]. Available: https://comtrade.un.org/data/

[12] Mongolia and coal [Online]. Available: https://www.gem.wiki/Mongolia_and_coal

[13] The annual report 2016, geology mining petroleum heavy industry [Godovoy otchet 2016, geologiya dobychi nefti, tyazhelaya promyshlennost'] Mineral resources and petroleum authority of Mongolia, Ulaanbaatar, 2017, 148 p. Ru.

[14] Coking Coal Industry Chain Summit, Report «Aspire Mining LLC», July 2011,QINGDAO, China. [Online]. Available: https://www.aspiremininglimited.com/userfiles/file/267_20110707%20coking%20coal%20industry%20chain%20summit%20presentation.pdf

[15] Ovoot coking coal project [Online]. Available: https://aspiremininglimited.com/ovoot-coking-coal-project/)

[16] Sereeter Jigjee, Odgerel Ulziikhutag, Transport challenges and opportunities for Mongolia, 2018, 20 p. [Online]. Available: http://www.unescap.org/sites/default/files/11%20Mongolia.pdf)

[17] Key parameters of the largest specialized coal port terminals in the world / Expert Online. Moscow, 10.03.2020 [Online]. Available: https://expert.ru/ratings/klyuchevyie-parametryi-krupnejshih-spetsializirovannyih-ugolnyih-portovyih-terminalov-v-mire/ Ru.

[18] Mongolian business [Online]. Available: https://krasugol.ru/novosti/452-biznes-po-mongolski)

[19] Southern Mongolia Infrastructure Strategy/ The International Bank for Reconstruction and Development / The World Bank. -138 p. [Online]. Available: https://siteresources.worldbank.org/INTMONGOLIA/Resources/SMIS_July.pdf

[20] Rygzynov T. Sh., Batomunkuev V.S., Luvsanzhantsangiin Erdenebayar. Development of the transportation infrastructure of Mongolia under a modern transformation of the economy / Mathematical and Instrumental Methods of Economics / MES, 11/2015 [Online]. Available: http://uecs.ru/uecs-83-832015/item/3786-2015-11-03-08-18-39?pop=1&tmpl=component&print=1

[21] Namsray Namjildorzh Intensification of cargo transportation through the network of JSC "Ulan-Bator Railway" for 2020 [Intensifikatsiya perevozok gruzov po seti AO«Ulan-Batorskaya zheleznaya doroga» na 2020 god] Sovremennye tekhnologii. Sistemnyi analiz. Modelirovanie [Modern Technologies. System Analysis. Modeling], 2018, No. 4 (60), pp. 132–138. Ru.

[22] Ulziinorov Gansukh, Xu Ming, Syed Ahtsham All Analysis of the Current Situation of Mongolian Railway and Its Future [Ves' analiz sovremennogo sostoyaniya zheleznoy dorogi Mongolii i yeye budushchego] Development International Business Research. –vol. 11, no. 5. pp.119–128 –2018 ISSN 1913-9004 E-ISSN 1913-9012. Ru.

[23] Bayasgalan Davaaseren Transit transportation of oil and gas processing products through the territory of Mongolia [Tranzitnyye perevozki produktsii nefte i gazopererabotki cherez territoriyu Mongolii] Sovremennye tekhnologii. Sistemnyi analiz. Modelirovanie [Modern Technologies. System Analysis. Modeling], 2018, no. 2 (58), pp. 64–72. Ru.

[24] Bayasgalan Davaaseren Justification for the construction of a second railway line between Mongolia and China [Obosnovaniye neobkhodimosti stroitel'stva vtoroy zheleznodorozhnoy linii mezhdu Mongoliyey i Kitayem] Sovremennye tekhnologii. Sistemnyi analiz. Modelirovanie [Modern Technologies. System Analysis. Modeling], 2018, No. 4 (60), pp. 56–63. Ru.

[25] The concept of implementing a joint Russian-Mongolian project for the development of JSC 'UBTZ' and the construction of new railway infrastructure in Mongolia [Kontseptsiya realizatsii sovmestnogo rossiysko-mongol'skogo proyekta razvitiya AO "UBTZ" i stroitel'stva novoy zhelezno-dorozhnoy infrastruktury v Mongolii] [Online]. Available: http://www.rzd.ru/main/public/ru/accessible). Ru.

[26] Ana-Maria Seman MONGOLIA'S ENERGY SECTOR: time for a rethink APRIL 2017, 40 p. [Online]. Available: https://bankwatch.org/wp-content/uploads/2017/06/Mongolia-energy-sector-web.pdf

[27] BP Energy Outlook: 2019, 14 February 2019, [Online]. Available: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/news-and-insights/press-releases/bp-energy-outlook-2019.pdf

[28] International Energy Outlook 2017, September 14, 2017, U.S. Energy Information Administration, [Online]. Available: www.eia.gov/ieo

[29] Annual Energy Outlook 2019 with projections to 2050, January 24, 2019, U.S. Energy Information Administration, [Online]. Available: www.eia.gov/ieo,www.eia.gov/aeo

[30] World Energy Outlook 2018, Flagship report — November 2018, U.S. Energy Information Administration, [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2018, http://www.mongolnow.com/hoshoot-krupnejshee-ugolnoe-mestorozhdenij-v-azii/

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An Improved Two-Stage Optimization Procedure for Optimal Power Flow Calculation

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***Abstract* — The paper focuses on the problem of optimal power flow. Minimized production and transmission costs were considered to design an optimal power flow search method based on the novel two-stage optimization procedure that takes into account the voltage and power constraints. As a result, the efficient optimum search method for the non-convex optimal power flow problem is proposed and implemented. The efficient L-BFGS-B optimization algorithm is employed to allow for the constraints. The stochastic modification of the global optimization algorithm of the Lipschitz function was used in the first stage to improve the L-BFGS-B method. Two illustrative examples on the IEEE 118-bus test scheme and real regional grid demonstrate the efficiency of the proposed two-stage optimization procedure. The possibility of taking into account the renewable sources in the proposed optimal power flow algorithm is briefly discussed**

***Index Terms* — optimal power flow, power system control, power system modeling, renewable energy sources.**

I. Introduction

Optimization of power system operation involves the determination of an optimal steady state in terms of minimized production and transmission costs. This paper proposes a two-stage optimization procedure taking into account voltage and power constraints. This is a non-convex problem as demonstrated below. A method of global and local optimum search is suggested to find a solution to the optimal power flow (OPF) problem. The proposed method allows taking into account the constraints using the L-BFGS-B (Limit memory version of Broyden Fletcher Goldfarb and Shanno optimization method with Border constraints) optimization algorithm.

The power systems operation optimization under various constraints has been fairly well addressed by many authors in the literature. On the one hand, many methods were designed and applied including the gradient descent, Newton method, the interior points method, conjugate gradients, and Lagrange relaxation [1-4]. Various artificial intelligence (AI) methods have been also widely used during the last decades. These are multi-agents systems, artificial neural networks, genetic algorithms, evolutionary programming, fuzzy logic-based control, particles swarm optimization, and many others [5-7]. On the other hand, many flexible control strategies have been recently proposed to cope with flexible modern power systems with renewable generation and storage [8-9].

It is worth noting that the efficient optimization of power flow remains a challenging problem especially for the power systems with a high share of renewables. Moreover, unstable low-frequency inter-area oscillations [10], caused by high level of renewable energy penetration, may have a severe negative effect on the objective function of optimal power flow and maximum power transfer.

The following challenges are under attacks most often:

1. Minimization of energy losses with the following control actions:
   a. Active and reactive power redistribution;
   b. The tap-changers adjustment;
   c. The shunt reactors and capacitor banks states' adjustment;
2. Change in overflows on transmission lines due to the FACTS devices.
3. Power flow adjustment for the operating conditions to meet voltage and flow constraints.
4. Optimization of active power generation according to economic criteria.

In this paper, our results [11] are further developed based on a new two-stage optimization procedure and the L-BFGS-B algorithm, namely:

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http://dx.doi.org/10.38028/esr.2020.01.0005
Received January 16, 2020. Revised March 20, 2020.
Accepted May 30, 2020. Available online July 31, 2020.

1. The global optimization and the local L-BFGS-B optimization methods are employed in the new software implementation of the proposed method. The flowchart of the generalized algorithm is presented in section V.
2. More representative calculations on the same test schemes are carried out.

The paper is structured as follows. The problem statement is given in Section II. The non-convex OPF problem is addressed in Section III. Section IV proposes a stochastic global optimization algorithm to improve the conventional L-BFGS-B method. Section V describes the application of the L-BFGS-B method. Case studies on two test schemes are given in Section VI. Section VII describes further research, in particular, a study on the possibility of including renewable sources in the optimization. Finally, Section VIII presents the concluding remarks.

II. Problem statement

The optimal power flow methods most often use only one criterion either minimization of generation cost or minimization of losses. This paper employs a complex optimization criterion and takes into account the cost of generation, losses in a grid, and voltage magnitude deviation [36]. Generation cost here is understood not as actual cost expressed in cash equivalents, but as a dimensionless quantity taking into account the loading preferences of various generators. As a result, the OPF problem is formulated as follows:

$$\min f\left(p_g, u_g, k_t\right) \tag{1}$$

where the objective function *f* is

$$\begin{aligned} f = \sum_{i \in G}\left(c_{i2} p_{gi}^2 + c_{i1} p_{gi} + c_{i0}\right) + \\ + c_{\Delta P} \sum_{j \in B} \Delta p_j + c_U \sum_{k \in N} \Delta u_k{}^2 \end{aligned} \tag{2}$$

The control parameters in the OPF problem (2) are as follows: p_g, u_g, k are the generation of active power, the voltage at PU buses and transformer ratios, respectively. Here G is a set of generator buses, B is a set of branches, N is a set of buses, p_{gi} is the active power of the i-th generator, Δp_j is power losses on branch j, Δu_k is a voltage magnitude deviation at bus k.

The objective function is adjusted as follows: c_{i2}, c_{i1}, c_{i0} are constants adjusting the generation cost; $c_{\Delta P}$ is a constant which takes into account the transmission losses; c_u is a constant for voltage deviations on buses.

The constraints on control parameters are as follows:

$$\begin{aligned} p_{gi}^{min} \le p_{gi} \le p_{gi}^{max}, \quad & \forall i \in G \\ u_{gi}^{min} \le u_{gi} \le u_{gi}^{max}, \quad & \forall i \in G \\ k_{ti}^{min} \le k_{ti} \le k_{ti}^{max}, \quad & \forall i \in T \end{aligned} \tag{3}$$

Here G is a set of generator buses involved in optimization, T is a set of transformer branches involved in optimization. Assume that the dependent parameters Δp_j are power losses in the transmission lines and Δu_k are voltage deviations on buses. These parameters are calculated using the electric network system of equations. An original modification of the Newton-Raphson method with the selection of an optimal step was involved to calculate the power flow. The power flow calculation process takes into account other constraints, such as the P/Q curves of the generators. In this method, the bus voltage equations are written in Cartesian coordinates. This method was proposed in [12] and developed in [13]. Load flow equations in Cartesian coordinates are:

$$s = f_s(u),$$

Where $u = [u_{r1}, u_{i1}, \ldots, u_{rn}, u_{in}]$ is the vector of real and imaginary parts of bus voltages; $s = [P_1, Q_1, P_2, |V_2|^2, \ldots, |V_s|^2, \delta_s]$ is the vector of independent parameters: active and reactive power of PQ-buses; active power and voltage at PU-buses; voltage and phases at slack buses. Electric network equations can be written in a matrix form as follows:

$$s = -diag(u) Y u^T. \tag{4}$$

The matrix of coefficients Y is formed based on the conductivities between buses and shunt conductivities at buses [13].

III. Nonconvex optimization

The necessary Karush-Kuhn-Tucker conditions are in the core of many optimization methods for power systems operation optimization. Such necessary conditions can guarantee only a locally optimal solution in real-world applications such as the non-convex optimum power flow problem [14, 15]. It can be argued that the non-convexity of the optimization problem is determined by the nonlinear dependence on physical parameters (including power and voltage), and by the power flow parameters constraints.

The state-of-the-art studies have paid much attention to the development of high performance algorithms. Let us briefly outline the advances in this field. The nonlinear interior point algorithms are proposed in [14, 15]. The origin of the non-convexity of the given optimization problem is shown in [18, 19] where the limits of power flow stability are taken into account. In this case, the stability at each iteration of optimization is an additional constraint. The convex relaxation is proposed for solving the optimal power flow problem in [14, 20]. However, this approach may not be suitable for the large dimension schemes. As shown in [14], the EPS operation optimization is an NP-hard problem with the objective function usually assumed to be convex [14, 21] for the sake of simplicity.

Thus, many authors assume that the non-convexity of the optimal power flow problem arises only because of the need to take into account different constraints, for example, constraints imposed by the system operator to control the current power flow in EPS. This assumption was studied in the framework of this paper. A search for a local optimum for the complex networks was made, starting with various randomly obtained initial states within the feasible region of the power flow parameters.

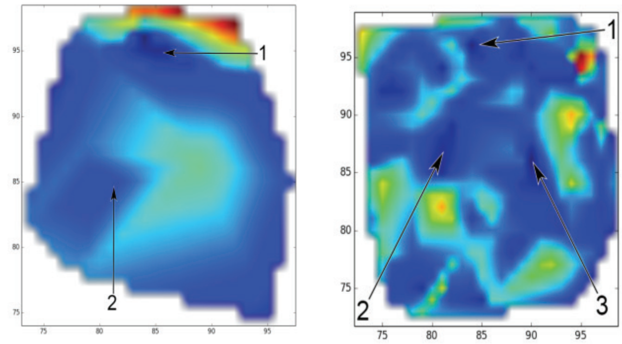


Fig. 1. The values of the objective function, shown by the intensity of the color (numerals denote the areas of local optima): a) for random search without optimization; b) with subsequent optimization.

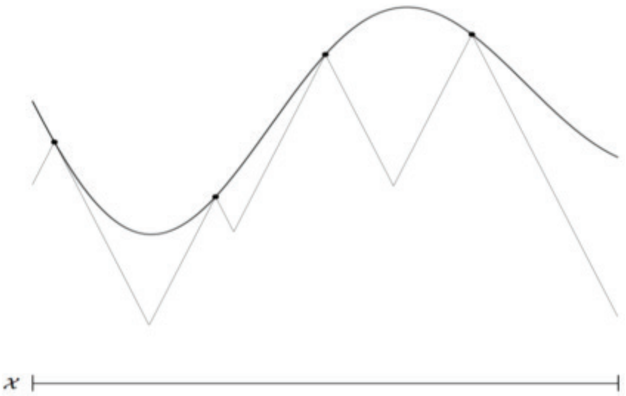


Fig. 2. AdaLIPO Algorithm illustration.

The calculation was carried out on the model of the Irkutsk region power system shown in Figure 4. The problem was simplified. In the objective function, we took into account only the terms responsible for network losses and voltage deviations. As control actions, only transformation ratios were used. At each random search iteration, random values of the control parameters from the feasible region were selected. After that, the power flow was calculated. In the case of convergence, the results were used as a starting point for local optimization by gradient descent algorithm. As can be seen, even in such a simplified case, the objective function is not convex.

The values of the objective function in the n-dimensional space of the control parameters were obtained, where n is the number of the control parameters. For clarity, Figure 1 shows the values of the objective function in the cross-section of the two most variable control parameters.

The calculations revealed the presence of several local optima. Therefore, to determine the scope of the local search it is necessary to employ the methods of global optimization. This will be addressed further.

IV. Global optimization algorithm

To find the global optimum, the search for regions of the local optimum is performed using the stochastic global optimization algorithm of the Lipschitz function (LIPOP), based on LIPO algorithm proposed in [22].

Since the discrete changes in EPS control parameters are assumed to be continuous, the optimization problem (1) can be considered as the optimization problem for the Lipschitz function.

In the AdaLIPO algorithm[22], a random sampling of points X_i from the feasible region of control parameters is made and the lower bound of the function is estimated from the closest points (as shown in Fig.2) using the Lipschitzness coefficient l:

$$x \to \max_{i=1..t} f(X_i) - l \cdot \|x - X_i\|_2, \tag{5}$$

Where X_i is the control parameters vector.

The coefficient is refined by the values of the objective function, as the maximum among the test points:

$$l = \max_{i\in T, j\in T, i\neq j} \frac{\left|f(X_i) - f(X_j)\right|}{\left\|X_j - X_i\right\|_2} \tag{6}$$

In order to increase the density of the test points in the region with a large gradient of the objective function and to reduce the number of tests in the region with small gradient values, a random search algorithm with the probability depending on the gradient is applied. The power flow is calculated only if the random sample $p \in [0,1]$ is less than the relative magnitude of the gradient g_i:

$$p_i < \frac{\|g_i\|}{\min_{i\in T}\|g_i\|}. \tag{7}$$

Here we call the modification of the LIPO algorithm LIPOP (P stands for "probability"). The Jacobian of the objective function was calculated in (7) by the numerical algorithm using Richardson extrapolation [23, 24].

The solution obtained by the global optimization method LIPOP can act as an initial approximation for performing local optimization by more accurate methods. Thus, the global optimization of the power flow can be carried out in two stages. In the first stage, the search is performed for the region with the least value of the objective function by global search in the feasible region. The second stage solves the problem of finding a local optimum with more precise methods.

V. Application of the BFGS methods

In this paper, the method based on the L-BFGS-B algorithm [25-27], which is a development of the BFGS method, is proposed as a method for finding a local optimum. This method is a quasi-Newton method that takes into account the constraints on the control parameters.

In this case, the constraints on power flow parameters are allowed for in two different ways. Control parameter constraints are taken into account in a standard way in the form of boundary conditions: $l \leq x \leq u$. Constraints on dependent power flow parameters are taken into account in the form of barrier functions, the values of which will be included in the general optimization objective function and will be calculated in the process of power flow calculation at each iteration of the optimization for the fixed values of the control parameters. The logarithmic functions are proposed to be used as barrier functions by analogy with the interior point method:

$$F(x) = -\sum\left(-b_i(x)\right), \tag{8}$$

where $b_i(x) \leq 0, i = 1, \ldots, m$ are dependent parameters constraints; m is the number of constraints.

This approach allows us to divide the optimization problem into the power flow calculation and the optimization problem itself. Due to the decomposition of the optimization problem into the power flow calculation and optimization, on the one hand, the constraints are simplified as follows $l \leq x \leq u$, on the other hand, in the framework of the power flow calculation at each iteration we can use complex network models including DC-lines, active filters, reactive power compensators, FACTS, and other devices.

As a result, the algorithm for finding the local optimum by the L-BFGS-B method is as follows:

1. At each step of the iterative process, we have the control vector x_k, the objective function value $f(x_k)$ and the gradient of the objective function g_k calculated at point x_k.
2. The gradient projection method is used to meet the constraints $l \leq x \leq u$.
3. The quadratic model of function f is calculated as follows:

$$m_k(x) = f(x_k) + g_k^T \cdot (x - x_k) + \\ + \frac{1}{2}(x - x_k)^T \cdot B_k \cdot (x - x_k), \tag{9}$$

where B_k is the Hessian approximation obtained by the quasi-Newton algorithm L-BFGS [28, 29]. Next, we determine a piecewise linear function that coincides in the direction with the antigradient and takes into account the constraints:

$$x(t) = P(x_k) - t \cdot g_k, l, u \tag{10}$$

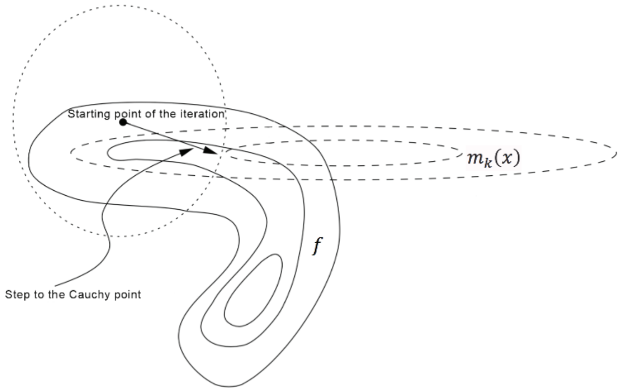


Fig. 3. Movement in the chosen direction.

Where

$$P(x, l, u)_i = \begin{cases} l_i, & if\ x_i < l_i \\ x_i, & if\ x_i \in [l_i, u_i] \\ u_i, & if\ x_i > u_i \end{cases} \tag{11}$$

The next step is the calculation of Cauchy point as the local minimum of the model function for the selected piecewise- linear direction (as shown in Figure 3):

$$x_c = \underset{x}{\operatorname{argmin}}\, m_k\left(x(t)\right), \tag{12}$$

The iterative process continues while the change in the control vector in the direction of optimization is greater than the selected threshold $\|x_k - x_{k-1}\| > \varepsilon$.

In the process of optimization, there can be situations when the power flow does not exist, for example, due to the power flow constraints. In this case, it is necessary to find the limiting state along the given trajectory and set new constraints.

The movement along the trajectory is performed by dividing the increments of the vector of the control actions in half. The quadratic model (9) in this case is written as:

$$m_k(x) = f(x_k) + g_k^T \cdot \Delta x + \frac{1}{2}\Delta x^T \cdot B_k \cdot \Delta x \tag{13}$$

here $\Delta x = \frac{x - x_k}{2\alpha}$, α, is the multiplicity of the step division.

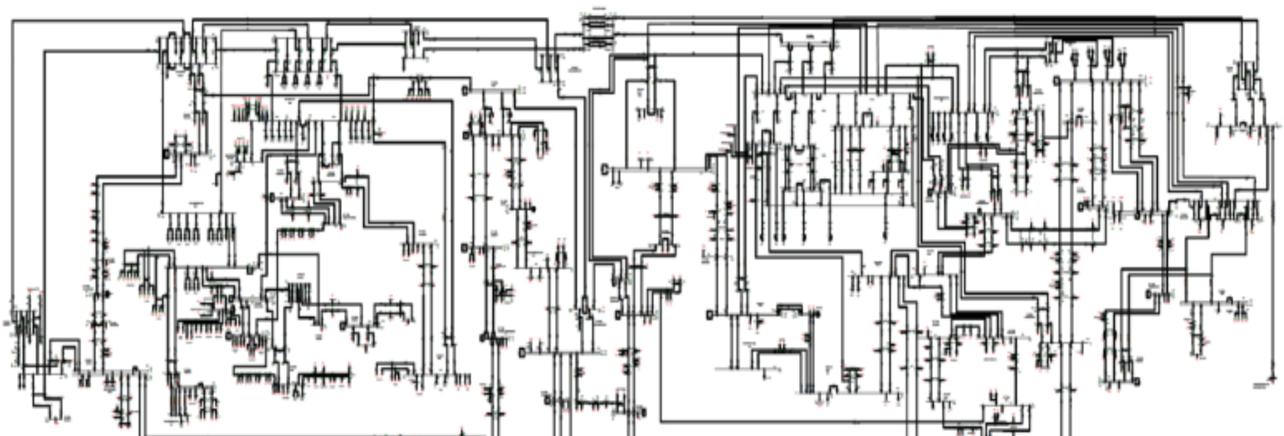


Fig. 4. Real power grid.

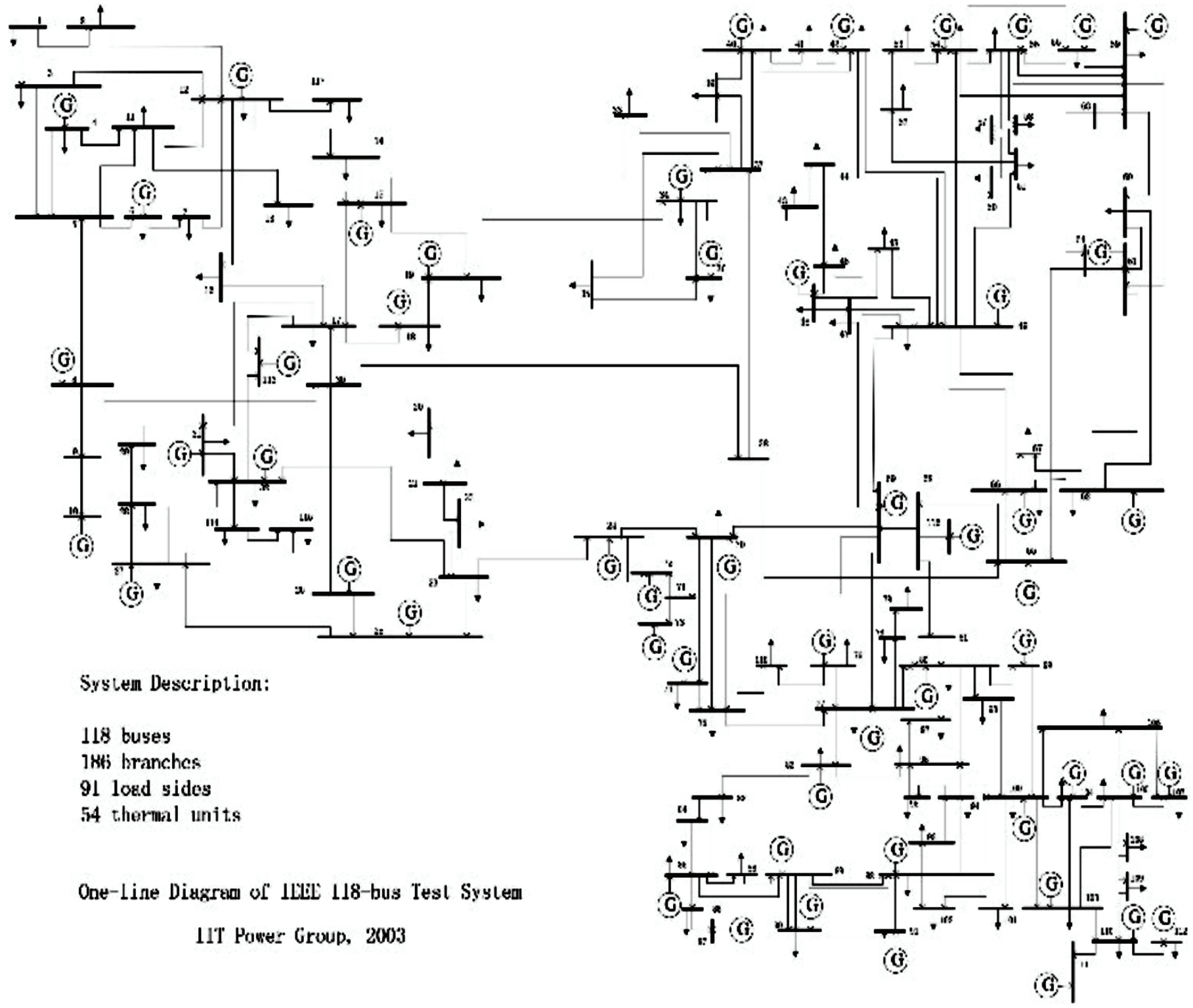


Fig. 5. IEEE 118 bus test system.

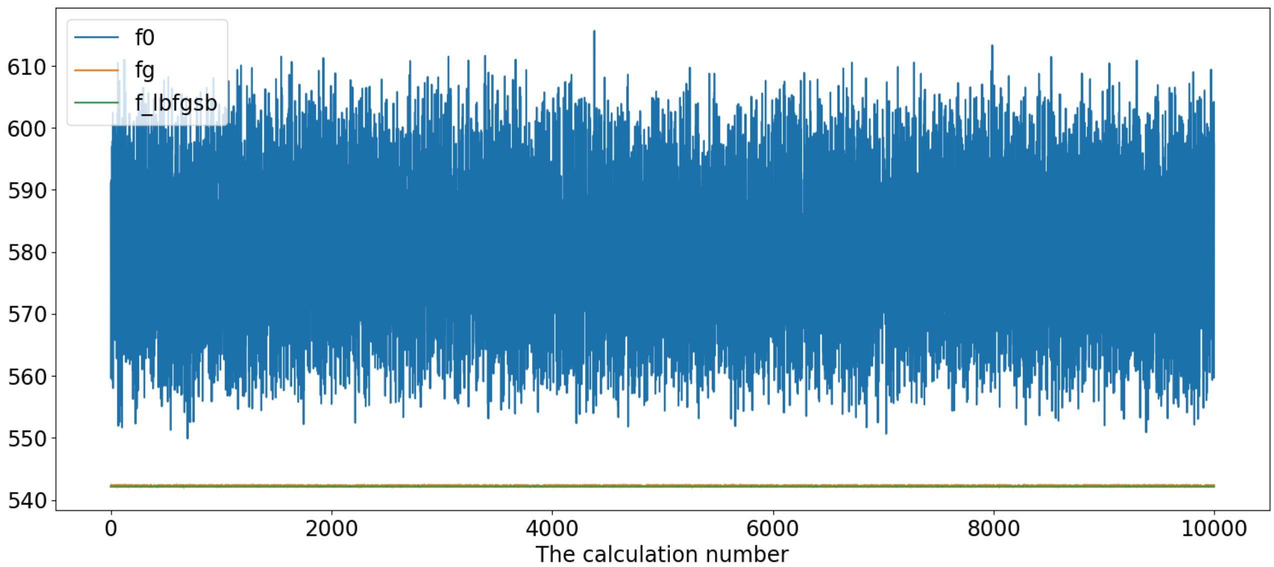


Fig. 6. Calculation results on the IEEE 118-bus test system.f_0 is an initial value of the objective function in p.u.; f_g is the objective function after gradient descent in p.u.; f_{lbfgsb} is the objective function after L-BFGS-B optimization in p.u. The ordinate axis is a serial number in a series of calculations with different initial states.

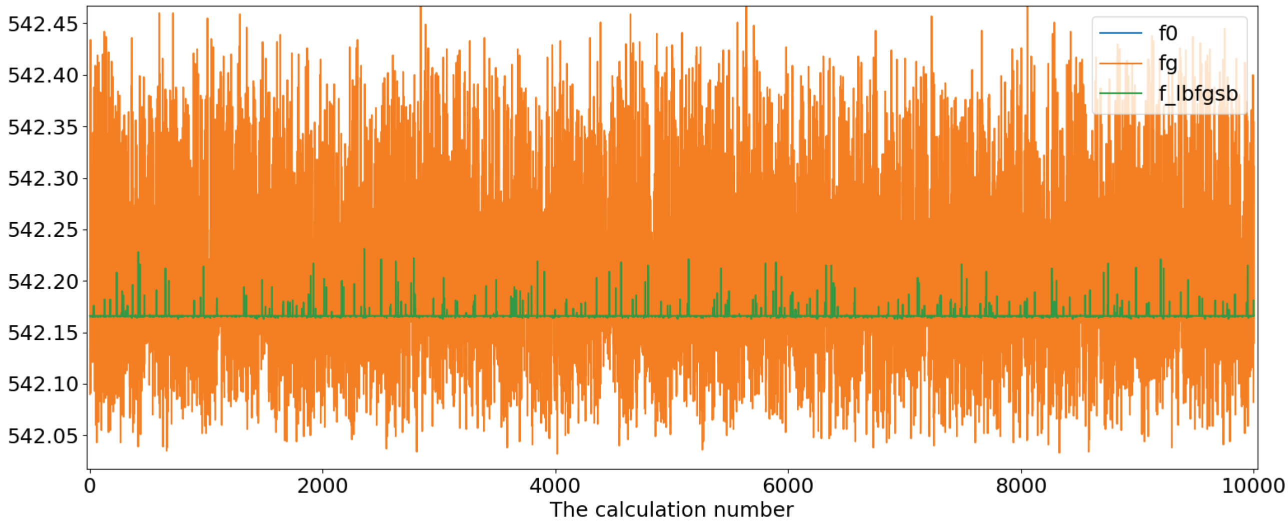


Fig. 7. Objective function after optimization on the IEEE 118-bus test system. f_g is the objective function after gradient descent in p.u.; f_{lbfgsb} is the objective function after L-BFGS-B optimization in p.u. The ordinate axis is a serial number in a series of calculations with different initial states.

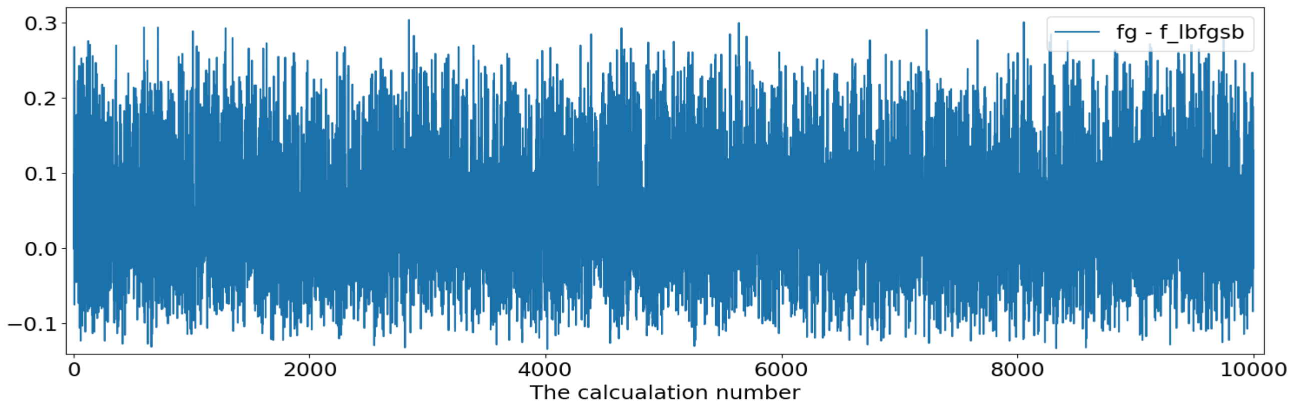


Fig. 8. Difference between objective functions in gradient descent and L-BFGS-B methods on the IEEE 118-bus test scheme. The ordinate axis is a serial number in a series of calculations with different initial states.

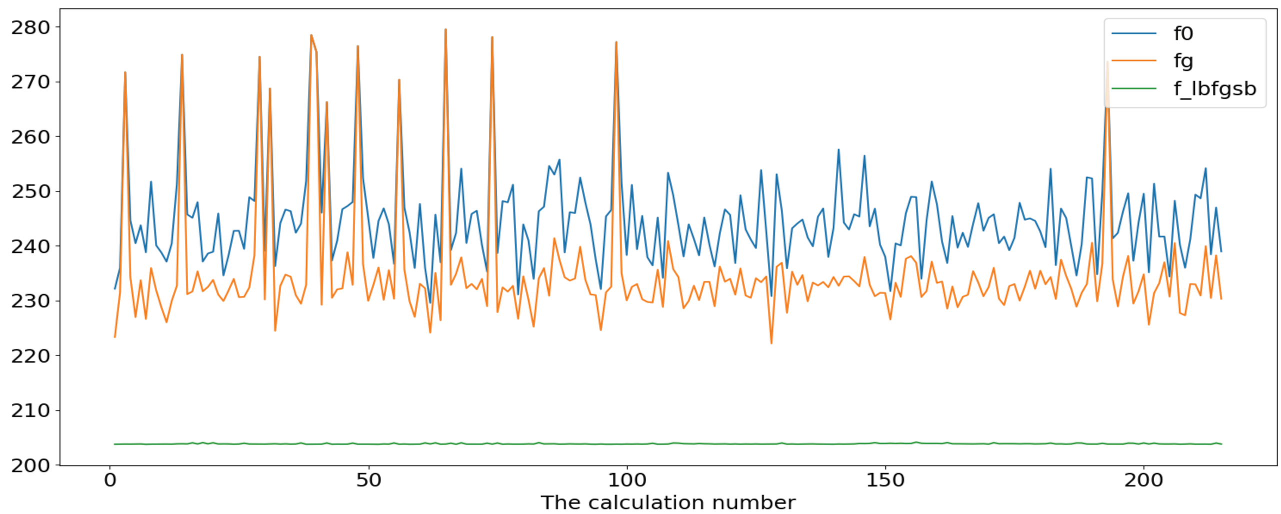


Fig. 9. Calculation results on Irkutsk region network model without constraints. f_0 is the initial value of the objective function in p.u.; f_g is the objective function after gradient descent in p.u.; f_{lbfgsb} is the objective function after L-BFGS-B optimization in p.u. The ordinate axis is a serial number in a series of calculations with different initial states.

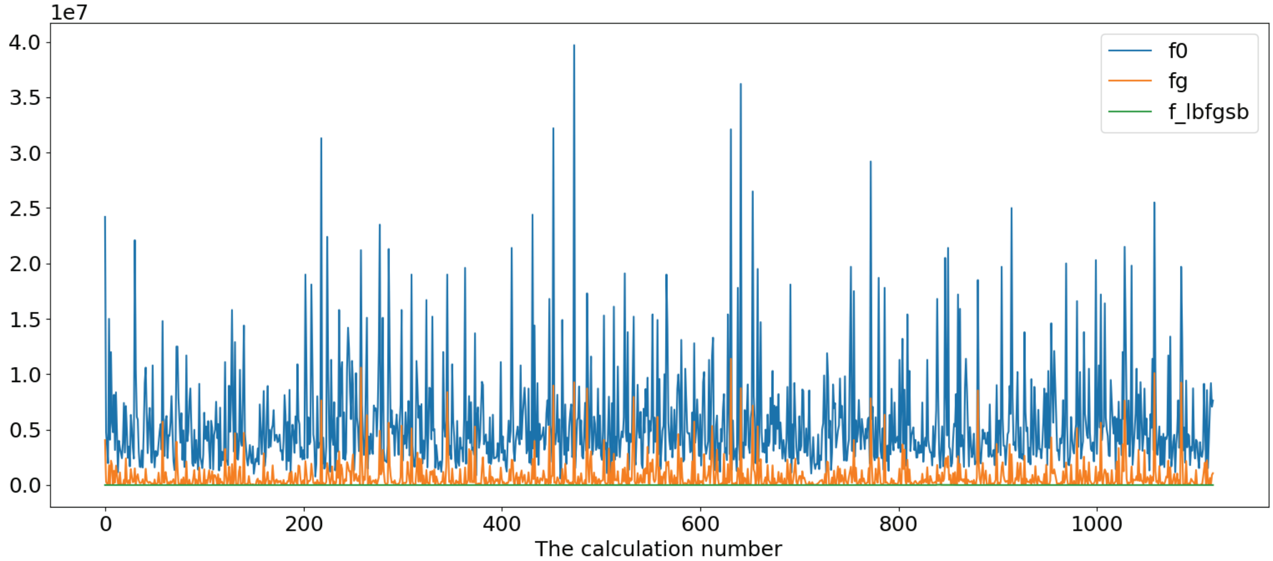


Fig. 10. Calculation results on the Irkutsk region network model with constraints. f_0 is the initial value of the objective function in p.u.; f_g is the objective function after the gradient descent in p.u.; f_{lbfgsb} is the objective function after L-BFGS-B optimization. The ordinate axis is a serial number in a series of calculations with different initial states.

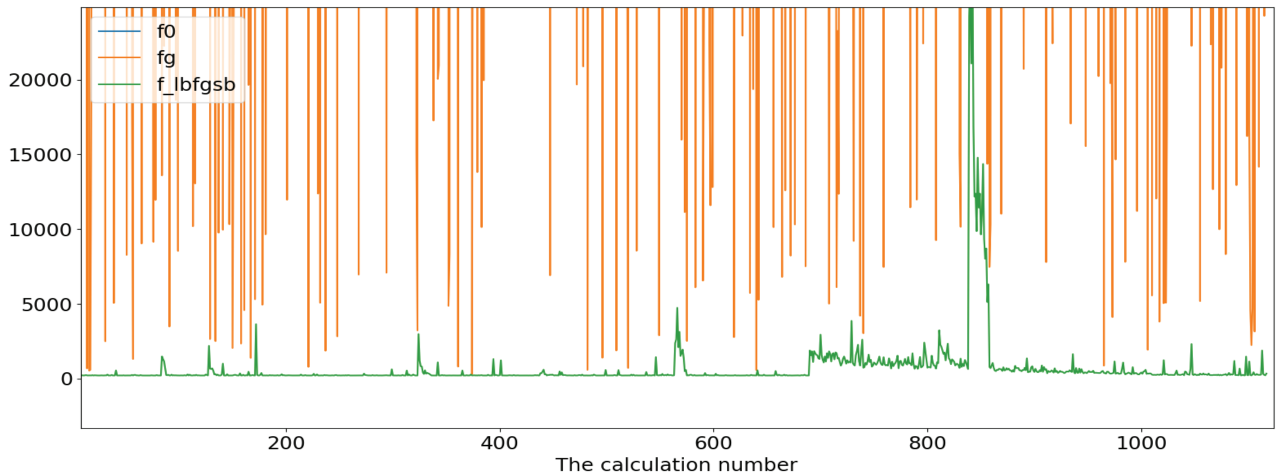


Fig. 11. A scaled plot of calculation results on the Irkutsk region network model with constraints. f_g is the objective function after the gradient descent in p.u.; f_{lbfgsb} is the objective function after L-BFGS-B optimization. The ordinate axis is a serial number in a series of calculations with different initial states.

The resulting flowchart of the proposed algorithm is as follows:

1. Perform global LIPOP optimization restricted by the number of iterations:
   1.1. Sample randomly control parameters from the feasible region according to (7).
   1.2 Calculate the objective function (1).
   1.3 Calculate the objective function.
   1.4 Save points with the lowest value of the objective function in the restricted *vector of global optimization results*.
2. Perform local optimization with L-BFGS-B for every point from the vector of global optimization results.
3. Select the optimal point from the results of local optimization.

VI. Case study

The proposed optimization scheme was tested on the IEEE 118- bus test system (shown in Figure5), and on the model of the Irkutsk region network (shown in Figure 4).

About 10000 series of calculations were performed. A random value of the vector of the control parameters is selected as a starting point within the feasible range where it was possible to calculate the steady state. The ordinate axis in the following Figures represents the values of the objective function in per units. The abscissa axis corresponds to a series of calculations from different starting points.

The results with a well-chosen step in the gradient descent optimization method on the IEEE 188-bus test scheme are quite close to the results of L-BFGS-B algorithm (Figure 6), however, the calculation results obtained using L-BFGS-B are more stable (Figure 7) and on average give a 4% better result (Figure 8).

A more vivid result is observed on the model of real electrical networks. If the optimization is performed on a model without constraints, the result of the L-BFGS-B algorithm is stable and several times better than the gradient descent (Figure 9). If the algorithm takes into account the constraints on the bus voltage, the application of the L-BFGS-B algorithm becomes even more effective (Figures 10-11). On a larger scale plot (Figure 11), it can be seen that L-BFGS-B method gives adequate results with a minimum objective function for almost all initial conditions, while the gradient descent for most of the initial states only slightly improves the objective function relative to the initial one (Figure 11).

This difference in the results can be explained by the fact that the model of the real power system has worse convergence of the initial state, and the gradient descent here is more sensitive to the initial descent step.

The speeds of the optimization algorithms are comparable. Thus, in the scheme of a real electrical network, the average operating time of the gradient optimization method is about 120 msec, and that of the L-BFGS-B algorithm is about 500 msec.

VII. Further studies

The development of micro-grids and renewables requires total rethinking of the EPS steady-state optimization. Wind and solar power plants are the major renewable energy sources (RES). The development of reliable power systems with high penetration of renewables is one of the challenges in modern power engineering. Such systems heavily depend on the weather conditions, which can be taken into account in the OPF problem in two different ways. The first approach is the generation forecasting based on the meteorological forecasts. In this approach, the optimization problem is divided into the classic problem of the optimal state search based on the given constraints and the problem of states prediction [7, 30, 31]. The second approach is based on the probabilistic calculation of the optimal power flow. In this case, the RES generation is given by the models that take into account the time-dependent probabilistic characteristics of generation as well as load. This is not only due to the variability of the traditional residential and industrial loads but also because the load can be active and can be influenced by the local RES such as small wind turbines and PVs (so-called electricity prosumers load) and storages [8].

The load model is usually given by a normal distribution with an average value and a standard deviation. The model of the wind power plant uses the Weibull distribution [31] to determine the probability of the wind speed, which is used to calculate the generation distribution of the wind power plant. The power distribution of the solar power plant is calculated using the beta-distribution function describing the solar irradiance [5, 33].

The probabilistic models of RES can be used to obtain the time distribution of generation as the function of time and installed generation capacity $\mathbb{p}_g(t, P_g)$. In this case, the objective function $f(\cdot)$ in (1) is as follows:

$$\sum_{i\in G}\left(c_{i2}p_{gi}^2 + c_{i1}p_{gi} + c_{i0}\right) + c_{\Delta P}\sum_{j\in B}\Delta p_j + c_U\sum_{k\in N}\Delta {u_k}^2 + \sum_{r\in R} c_{gr}\,\mathbb{p}_{gr}(t, P_{gr})P_{gr}\,. \quad (14)$$

The vector of independent parameters in the network equations (4) includes the power of RES generation and loads, given the corresponding probability distributions:

$$s = [\mathbb{p}_l(t, P_l)p_l, q_l, \mathbb{p}_g(t, P_g)p_g, q_g, p_g, u_g, \delta_g]^T. \quad (15)$$

The optimal power flow calculations take into account the probabilities. Such calculations are performed using the two-point estimation method proposed by Verbic [34]. The essence of this method is as follows. For each value of generation and load given by the probability, two optimal power flows corresponding to values below and above the average are computed. The remaining probabilistic variables are selected as the mean value. Based on these two points, the vector of control parameters is estimated for each probability value.

The calculation of the optimal power flow, considering the probabilities, requires a significant number of deterministic optimal flow distribution calculations. Finding an optimal power flow for a certain time range is a more complicated problem. In this case, the dynamic optimization problem can be formulated as follows:

$$\min f(t_0, T, x) = \int_{t_0}^{t_0+T} f_p(t, x)dt + f_t\left(\left\| x_{t_0-T} - x_{t_0+T}\right\|\right), \quad (16)$$

Where t_0 is the initial time, T is the optimization time horizon, f_p is the objective function calculated for each moment by the method of probabilistic optimal flow distribution, f_i is the cost function of the transition from the initial state to the optimal one, determined as:

$$f_t(x) = c_t\sum_{x\in X} 1, x > 0. \quad (17)$$

Thus, the method of deterministic optimization is used in each stage of dynamic and probabilistic optimization.

VIII. Conclusion

The paper proposes an efficient two-stage optimization procedure based on the stochastic modification of the global optimization algorithm of the Lipschitz function and the L-BFGS-B method. The L-BFGS-B algorithm has a super-linear convergence rate. The complexity of the designed optimization algorithm is $O(n_2)$.

The decomposition of the calculation of the optimal power flow for the steady-state calculation problem and the optimization algorithm itself made it possible to efficiently perform optimization without complicating the optimal power flow calculation.

The presented optimization technique was implemented in the ANARES software [35]. The calculations on the models of the Irkutsk regional network revealed the following advantages. In comparison with the gradient method, the L-BFGS-B method of local optimization does not require to set an optimization step. The global optimization makes it possible to reach the global minimum of the objective function in a feasible region of the control parameters.

IX. Acknowledgments

This research has been carried out within the program of fundamental research of Siberian Branch of the Russian Academy of Sciences and within the framework of the research projects III.17.3.1, III.17.4.2, No. AAAA-A17--117030310442-8, No. AAAA-A17-117030310438–1. The authors are thankful to anonymous reviewers for their useful comments to improve the presentation and quality of the paper.

References

[1] Yu. Nesterov, A. Nemirovski, “Interior-point aplynomial algorithms in convex programming,” *SIAM Studies in Applied Mathematics*, vol. 13. 1993.

[2] Yu. Nesterov, “Introductory lectures on convex optimization: A basic course,” Springer, 2013.

[3] S. Wright, J. Nocedal, “Numerical optimization,” Springer Science, 2006.

[4] V.I. Zorkaltsev, “Dual interior points algorithms,” *Russian Mathematics*, vol. 55, no. 4, pp. 26–43, 2011.

[5] J.A. Momoh, “Electric power system applications of optimization,” CRC Press, 2008.

[6] J.A. Momoh, R. Adapa, M.E. El-Hawary, “A review of selected optimal power flow literature to 1993. I. Nonlinear and quadratic programming approaches,” *IEEE transactions on power systems*, vol. 14, no. 1, pp. 96-104, 1999.

[7] F. Liu, L. R. Li, Y. Li, Y. Cao, D. Panasetsky, D. Sidorov, "*Short-term wind power forecasting based on TS fuzzy model*", *In 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference* (APPEEC), pp. 414-418. IEEE, 2016.

[8] Y.Li, L. He, F. Liu, C. Li, Y. Cao, M. Shahidehpour, "Flexible voltage control strategy considering distributed energy storages for the dc distribution network," *IEEE Transactions on Smart Grid*, vol. 10, Issue: 1, Pages: 163 – 172, Jan. 2019.

[9] Y. Li, L. He, F. Liu, Y. Tan, Y. Cao, L. Luo, M. Shahidehpour, “A dynamic coordinated control strategy of WTG-ES combined system for short-term frequency support,” *Renewable Energy*, vol. 119, pp 1-11, 2018.

[10] D. Sidorov, D. Panasetsky, and V. Šmádl, "Non-stationary autoregressive model for on-line detection of inter-area oscillations in power systems," *2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*, Gothenberg, 2010, pp. 1-5.

[11] A. Domyshev, D. Sidorov, D. Panasetsky, Y. Sun, P. Ju, and F. Wu, "Optimal Power Flow Calculation Using BFGS-Based Optimisation Scheme," *Proc. Of 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2)*, Beijing, pp. 1-6, 2018.

[12] Iwamoto, S., Y. Tamura, “A load flow calculation method for ill-conditioned power systems,” *IEEE transactions on power apparatus and systems*, vol. 4, pp. 1736-1743, 1981.

[13] V.Z.Manusov, O.N.Shepilov, "Express methods of analysis of modes for assessing the reliability of electrical systems based on the Cartesian coordinate system,” SEI, Irkutsk, pp. 168-175, 1989 (in Russian).

[14] J. Lavaei, S.H. Low, “Zero duality gap in optimal power flow problem,” *IEEE Transactions on Power Systems*, vol.27, no.1, pp. 92-107, 2012.

[15] H. Wei et al. "An interior-point nonlinear programming for optimal power flow problems with a novel data structure," *IEEE Transactions on Power Systems*, vol. 13, no. 3, pp. 870-877, 1998.

[16] W.M. Lin, C.H. Huang, T.S. Zhan, “A hybrid current-power optimal power flow technique,” *IEEE Transactions on Power Systems*, vol. 23, no. 1, pp. 177-185, 2008.

[17] Q.Y. Jiang et al. “Power–current hybrid rectangular formulation for interior-point optimal power flow,” *IET generation, transmission & distribution*, vol. 3, no. 8, pp. 748-756, 2009.

[18] D. Gan, R.J. Thomas, R.D. Zimmerman, "Stability-constrained optimal power flow," *IEEE Transactions on Power Systems*, vol.15, no. 2, pp. 535-540, 2000.

[19] H.R. Cai, C.Y. Chung, K.P. Wong, “Application of differential evolution algorithm for transient stability constrained optimal power flow,” *IEEE Transactions on Power Systems*, vol.23, no.2, pp.719-728, 2008.

[20] X. Bai et al. “Semidefinite programming for optimal power flow problems,” *International Journal of Electrical Power & Energy Systems*, vol. 30, no.6-7, pp 383-392, 2008.

[21] S.H. Low, ”Convex relaxation of optimal power flow—Part I: Formulations and equivalence,” *IEEE Transactions on Control of Network Systems*, vol. 1, no. 1, pp. 15-27, 2014.

[22] C. Malherbe, N. Vayatis, “Global optimization of Lipschitz functions,” *In Proceedings of the 34th International Conference on Machine Learning*, vol. 70, pp. 2314-2323, 2017.

[23] P. Deuflhard, “Recent progress in extrapolation methods for ordinary differential equations,” *SIAM review*, vol. 27, no. 4, pp. 505-535, 1985.

[24] P.L. Fima, “Richardson Extrapolation: The Power of the 2-gon,” *Mathematics TODAY*, 2003. P. 159.

[25] R.H. Byrd, “A limited memory algorithm for bound constrained optimization,” *SIAM Journal on Scientific Computing*, vol.16, no.5, pp. 1190-1208, 1995.

[26] P. Armand, P. Ségalat. “A limited memory algorithm for inequality constrained minimization,” *Technical Report 2003-08*, University of Limoges (France) 2003.

[27] G. Yuan, X. Lu, "An active set limited memory BFGS algorithm for bound constrained optimization," *Applied Mathematical Modelling,* vol. 35, no. 7, pp. 3561-3573, 2011.

[28] D.C. Liu, J. Nocedal, “On the limited memory BFGS method for large scale optimization," *Mathematical Programming*, vol.45, no.1-3, pp.503-528, 1989.

[29] J.C. Gilbert, C. Lemaréchal, "Some numerical experiments with variable-storage quasi-Newton algorithms," *Mathematical Programming*, vol.45, no.1-3, pp.407-435, 1989.

[30] Y. Li, Z. Wen, Y. Cao, Y. Tan, D. Sidorov, D. Panasetsky, "A combined forecasting approach with model self-adjustment for renewable generations and energy loads in smart community," *Energy*, vol. 129, pp.216-227, 2017.

[31] V.G. Kurbatsky, D.N.Sidorov, V.A. Spiryaev, N.V. Tomin, "The hybrid model based on Hilbert-Huang transform and neural networks for forecasting of short-term operation conditions of the power system," *IEEE Trondheim PowerTech*, Trondheim, 2011, pp. 1-7, 2011.

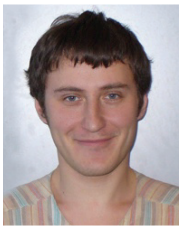
[32] Y. Yuan, J. Zhou, P. Ju, and J. Feuchtwang. "Probabilistic load flow computation of a power system containing wind farms using the method of combined cumulants and Gram–Charlier expansion," *IET renewable power generation*, vol. 5, no. 6, pp. 448-454, 2011.

[33] N. Nikmehr, S.N. Ravadanegh, "Heuristic probabilistic power flow algorithm for microgrids operation and planning," *IET Generation, Transmission &Distribution*, vol. 9, no.11, pp. 985-995, 2015.

[34] G.Verbic, C.A. Canizares, “Probabilistic optimal power flow in electricity markets based on a two-point estimate method,” *IEEE transactions on Power Systems*, vol.21, no.4, pp. 1883-1893, 2006.

[35] “Software package for power system modeling,” [Online]. Available in RUSSIAN: http://anares.ru/software

[36] Huang C. M. et al., “Comparative study of evolutionary computation methods for active–reactive power dispatch,” *IET generation, transmission & distribution,* vol. 6, no. 7, pp. 636-645, 2012.



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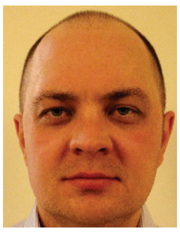

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Reliability Assessment of Electric Power System with Distributed Generation Facilities

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***Abstract* — Modern power supply systems that have distributed generation and are connected to the electric power system, renewable energy sources, and storage devices, require changes in the assessment of their reliability indices. The complexity of the energy, technological, and organizational structures of power systems with distributed generation does not allow the traditional concept of "failure" to be used to assess their reliability. Many technological solutions used in the distributed generation projects can become sources of vulnerabilities in the infrastructure of an intelligent electrical network. The study shows that power systems with distributed generation are the structures with overlapping service areas, which determines their specific features represented by an integral characteristic - efficiency. It characterizes the extent to which the use of distributed generation facilities in various operating conditions is feasible. The paper proposes an approach to quantifying the efficiency of such systems. The presented examples demonstrate the calculation of relatively simple power systems with the distributed generation that perform several tasks simultaneously.**

***Index Terms* — distributed generation, electrical system, efficiency, reliability, power supply, structure**

I. Introduction

A specific feature of power systems with distributed generation (DG) is the complexity of their energy, technological, and organizational structure, which allows, on the one hand, performing a set of tasks to ensure reliable and efficient power supply to consumers, and on the other hand, ensuring stable operation when the individual generating units (GUs) and their groups fail. Changes in the structure of the DG-based power system due to failures of groups of units and tie lines between them only decrease its performance indices, since the boundaries between operating and non-operating, as well as between operating, partially operating and non-operating states, are blurred and often conventional [1].

This is due to the redundancy of the structure, the presence of back-up generating units (overlapping service areas), switching capabilities and connections, specific features of the operation of relay protection devices and emergency control systems, operation correction tools (reactive power compensation and voltage regulation), and possible errors of the staff. Therefore, there is no universally accepted concept of “failure” for such systems [1, 2]. An example of overlapping service areas can be the case when several companies have distributed generators that are connected to the public power supply system.

The representation of DG-based power systems by structures with several overlapping service areas determines the specific features of their operation. These can be estimated by an integral characteristic - the efficiency, i.e., the extent to which the use of the DG-based power system in various operating conditions is feasible. However, the issues related to the specific features of calculating the efficiency of the systems with overlapping service areas have not been fully studied [2–7], which determines the significance of the research and the need for the practical implementation of the method of overlapping areas.

Even in a state of full operability, the DG-based power system may fail to perform all its functions, which can be due to an unfavorable combination of circumstances (uneven power generation by renewable energy sources (RES), overload due to increased consumer demand, and unauthorized external impacts (cyberattacks)) [8].

It is worth noting that the behavior of autonomously working generating units in the power systems with distributed generation differs significantly from that within the system. In the latter case, the specific features of the hierarchical structure, operating conditions, and switching capabilities of the network; the interdependence of failures of individual components; the order of their recoveries, etc. can manifest themselves. This necessitates taking

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http://dx.doi.org/10.38028/esr.2020.01.0006
Received June 06, 2020. Revised July 01, 2020.
Accepted July, 17 2020. Available online July 31, 2020.

into account the behavior of the k-th component (xk), which is determined by the prehistory of part or all other components [4]:

$$x_k\,(t+dt) = f_k\,[xk\,(0,t),\; x_1(0,t),\ldots,x_n\,(0,t)]\,,$$

Where f_k is the function determined by the specific features of the system.

Then, the state of the system is determined by an n-dimensional random variable

$$X(t)=[x_1\,(t),x_2\,(\mathrm{t}),\ldots,x_n(t)],$$

whose path of behavior in the interval (t, t+θ) is an n-dimensional random function

$$X(t,\theta)=[x_1\,(t,\theta),x_2\,(t\theta),\ldots,x_n\,(t\theta)].$$

Therefore, it becomes necessary to expand the concept of "reliability" [9] and transition to the efficiency indices of a system with the distributed generation when it performs certain tasks in specific conditions [2–5]. The index of efficiency is a measure that quantitatively assesses the quality of how the DG-based power system fulfills the functions, that is, the measure of the utility of the DG-based power system functioning in a particular situation while supplying power to consumers under specific operating conditions of the generating units. In fact, the use of efficiency indices in the evaluation of the quality (extent) of performing their functions by complex electric power systems is a rather widely used approach.

It is worth noting that some of the reliability indices of complex power systems, for example, when assessing the adequacy, have a sense of efficiency indices (for example a mean value of undersupplied power).

II. Operating conditions of radial power supply system

1) By analogy with [10], we consider the simplest (autonomous) radial power supply system consisting of a conventionally failure-free source I (infinite bus), homogeneous consumers m, and identical power lines w (Fig. 1). We will define by s = 1-r the probability of a failure of the m_i-th consumer for the reasons that are not related to its power supply and by q =1- p a failure of the power line.

Since the failures of the consumer and power lines are independent, we conclude that the probability that consumer i is connected to the source is $P = rp$. The probability of a complementary event is. $Q = 1\text{-}rp$

Here, the distribution of the number of consumers connected to the source obeys the binomial law for which the mathematical expectation $M\,[m]$ and standard deviation are defined by

$$M[m] = mrp; \quad \sigma_m = \sqrt{D[m]} = \sqrt{mrp(1-rp)}\,.$$

2) The development of renewable energy sources and distributed generation systems causes the need to estimate the operating conditions of autonomous electrical systems consisting of several sources. Consider a scheme of an autonomous electric power system (Fig. 2) for which it is necessary to evaluate the reliability of power supply to essential consumers connected to the switchboard SB [11].

The structural scheme of this electric power system in the form of a graph (excluding circuit breakers) is shown in Fig. 3. Consumers receive power (operability of this power system) if the following conditions for normal operation are met: a) properly operating generator (G_1), main switchboard board (MSB_1), cable line W_1, switchboard (SB); b) properly operating G_1, MSB_1, W_3, MSB_2, W_2, SB; c) properly operating G_2, MSB_2, W_2, SB; d) properly operating G_2, MSB_2,W_3, MSB_1, W_1, SB.

$$A(v_1,v_2,v_3,v_4,v_5,v_6,v_7,v_8) = \left\|\begin{matrix} P_1 \\ P_2 \\ P \\ P_4 \end{matrix}\right\|$$

$$= \left\|\begin{matrix} v_1 & v_3 & v_5 & v_7 & & \\ v_1 & v_3 & v_8 & v_4 & v_6 & v_7 \\ v_2 & v_4 & v_6 & v_7 & & \\ v_2 & v_4 & v_8 & v_3 & v_5 & v_7 \end{matrix}\right\|$$

The same conditions will be written in a matrix form

3) The expansion of closed networks in DG-based

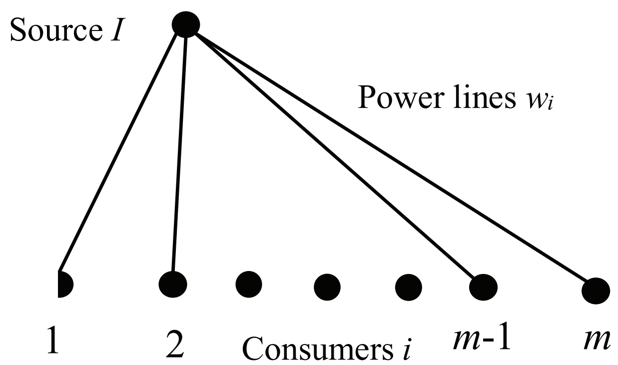

Fig.1. Radial power supply system with a power source.

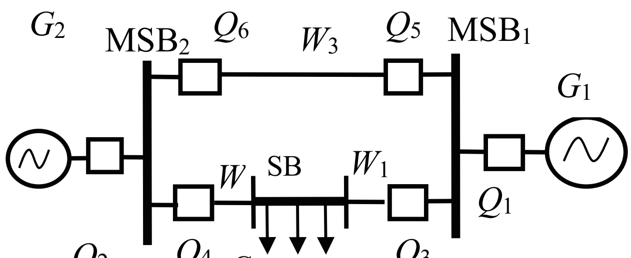

Fig. 2. Scheme of an autonomous electric power system.

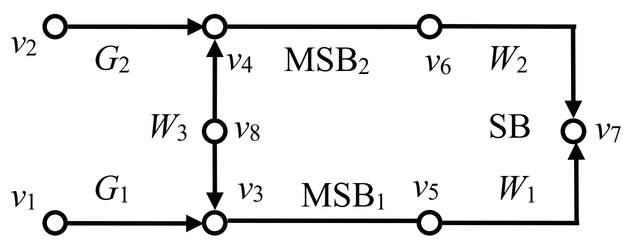

Fig.3 Graph of the scheme in Fig.2.

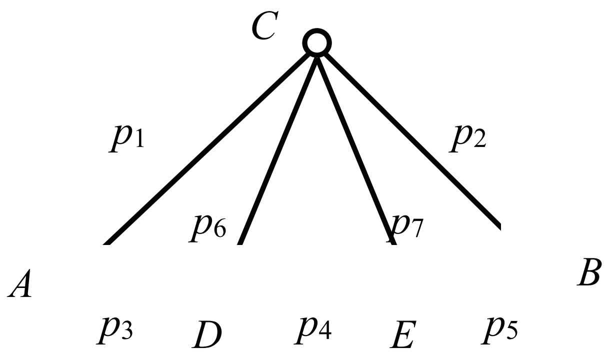

Fig. 4. Scheme of a conventional autonomous power system.

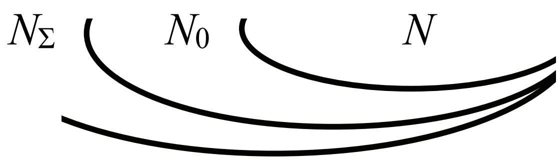

Fig. 5. A possible relationship between operating conditions of generating unit.

power systems requires an assessment of the probability of network connectivity. Figure 4 presents a graph of a similar system. The nodes of electricity generation, distribution, or consumption are the vertices of this graph, and the parameters of power transmission lines are the weights of edges that are equal to the probabilities of their operable state. In this statement, it is of interest to estimate the probability of network connectivity, for example, between nodes A and B. For simplification, all nodes are assumed to be reliable [10].

Suppose that for the tie line between nodes A and B, one can use all paths consisting of three or fewer edges connected in series. Then

$$\begin{matrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{matrix} \begin{Vmatrix} AC & CB & 0 \\ AD & DE & EB \\ AD & DC & CB \\ AC & CE & EB \end{Vmatrix}$$

The lack of the connection between nodes A and B is reduced to the calculation of the probability

$$Q_{AB}=(1-p_1 p_2)\cdot(1-p_3 p_4 p_5)\cdot(1-p_3 p_6 p_2)\cdot(1-p_1 p_7 p_5).$$

III. DG-based power systems with overlapping service areas

since any electric power system (EPS), including that with DG, belongs to the class of large systems with several levels of operation and is characterized by a complex structure, multi-functionality, and redundancy, it cannot be represented by single classical reliability indices. Failures of its components (in this case, generating units and tie lines between them) do not lead, as a rule, to the failure of the entire system but only reduce its efficiency.

In the simplest case [6], the efficiency is the probability that an autonomous generating unit will provide uninterrupted power supply to consumers. In this case, the efficiency coefficient E additionally acquires the meaning of probability that the performance of this task will not be disrupted due to the impossibility of providing some operating conditions (failures). We consider N_Σ to be a set of all possible operating conditions of generating unit aimed at providing power supply to consumers. N is a set of actually existing operating conditions. However, there can be some additional feasible conditions that together with N constitute a set of N_0. Then $N \in N_0 \in N_\Sigma$ (Fig. 5).

The efficiency here is the probability p that the operating condition n belongs to the set N, that is, $E = p\{n \in N\}$. Similarly, $E_0 = p\{n \in N_0\}$. The probability that the operating condition of generating unit simultaneously belongs to two sets N and N_0 will be

$$p\{n \in N, n \in N_0\} = p\{n \in N\},$$

because $N \subset N_0$ (Fig. 1).

According to the multiplication theorem of probability, we obtain

$$p\{n \in N, n \in N_0\} = p\{n \in N_0\} \cdot p\{n \in N | n \in N_0\}.$$

In this case, the efficiency coefficient is determined as

$$E = \frac{p\{n \in N\}}{p\{n \in N_0\}} = \frac{p\{n \in N, n \in N_0\}}{p\{n \in N_0\}} = p\{n \in N | n \in N_0\}. \quad (1)$$

The resulting expression (1) is the probability that power will be supplied to consumers in almost any operating condition of the generating unit.

Since it is difficult to obtain the estimates of the efficiency of the DG-based power systems, the need arises to develop and improve the appropriate mathematical apparatus. In general, the estimation of the DG-based power system efficiency $E_{syst}(t)$ is reduced to calculation using the formula proposed in [2]

$$E_{syst}(t) = \sum_{k=1} p_{X_k}(t) E_{X_k},$$

where $X = (x_1, x_2, \dots, x_n)$ is a DG-based power system state; n is the number of the system's components in two states (x_i = 1 – operable, x_i = 0 – failure); $p_{X_k}(t)$ is the probability that the system is in state X_k at time t; E_{X_k} is the efficiency of the system in state X_k.

When n is large, the efficiency calculation using (2) is quite complicated. Therefore, we consider the approach proposed in [2, 3, 5]. It is based on the fact that in an area, there are several generating units integrated into a system. They supply power to consumers not only to those directly connected to «their» generating unit but also (with a sufficient power reserve and transfer capability of the network) to the consumers connected to other units that are geographically close and located in the overlapping areas of adjacent generating units.

If in the system of n components with probability p_i

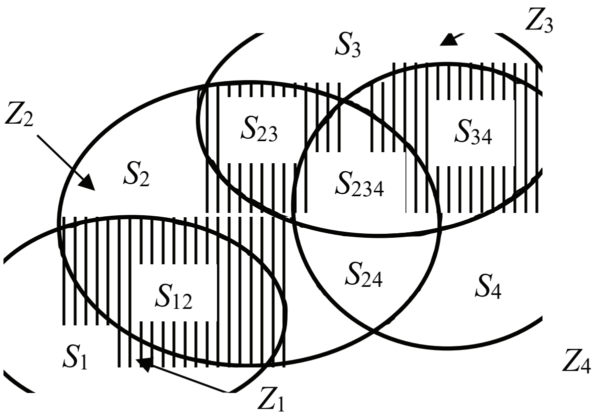

Fig. 6. Operating areas of generating units of the DG-based power system.

the *i-th* component is in an operable state, its service area includes area S_i. Service areas of two, three, etc. components can overlap and form areas $S_{i,j}, S_{i,j,k}, \dots, S_{i,j,k,\dots,n}$ with corresponding components of influence. In the general case, there can be 2^n such areas. The service area of the whole system is represented by the integration of all service areas of components $S = \bigcup_{i=1}^{n} S_i$ [2].

Suppose that a conventional power system represents a DG-based power system that consists of four generating units (power plants), each providing operation of electricity consumers of «its» service area. There are regions in each area, which overlap with adjacent two or more areas. Consequently, a system with overlapping service areas is formed.

Part of the area that does not overlap with others is denoted by $S_i, (i = \overline{1,4})$, and the regions of overlap are $S_{i,j}, S_{i,j,k}$ $(i = j = k = \overline{1,4})$. All highlighted regions define the service area S of a generating unit of the considered DG-based power system (Fig. 6).

Denote the efficiency coefficients of the highlighted regions by E with corresponding subscripts. If, for example, a generating unit whose main consumers are located in area Z_2 fails, the efficiency coefficients of the regions covered by this area will change. Instead of E_{12}, E_{23}, E_{24}, E_{234} we obtain E_1, E_3, E_4, E_{34}. Naturally, in each practical task, the efficiency coefficients for the regions of overlap are determined individually.

Such a division of operating area of the DG-based power system consisting of n generating units can significantly reduce the number of the considered regions relative to the value of 2^n, that is, it can simplify the calculation of E of the DG-based power system. The calculation of E is reduced to the calculation of the efficiency coefficients of each region and their weighted summing up given:

- power output from generating units;
- switching capabilities of power supply schemes;
- network operating parameters;
- composition, specific features of operation and settings of relay protection and emergency control systems;
- power consumption and process-related specific features of consumers located in the corresponding area;
- other indices characterizing the transition of the DG-based power system to limiting conditions.

The component of efficiency coefficient e_i in the resulting sum for area S_i without overlap S with other areas is found as

$$e_i = S_i E_i p_i,$$

where p_i is the probability of generating unit failure in area Z_i with the failure of power supply to consumers in area S_i.

The component for the region of overlap between areas Z_i and Z_j is equal to

$$e_{ij} = S_{ij}\left(E_{ij} p_i p_j + E_i p_i q_j + E_j q_i p_j\right)$$

The component formed by overlapping of three areas Z_i, Z_j and Z_k is

$$e_{ijk} = S_{ijk}(E_{ijk} p_i p_j p_k + E_{ij} p_i p_j q_k + E_{ik} p_i q_j p_k$$
$$+E_{jk} q_i p_j p_k +$$
$$+E_i p_i q_j q_k + E_j q_i p_j q_k + E_k q_i q_j p_k)$$

The efficiency coefficients of each region in the case of a larger number of areas are estimated similarly.

Note that the efficiency coefficient determines the average level of quality of the system operation, which depends on the reliability of its components. It can be dimensionless (probability of meeting the consumer requirements) and can have the dimension (the amount of generated power, the amount of consumption, profit, loss, etc.) In the case of generating unit failure in area Z_i, the losses (damage) are determined by consequences of the interrupted power supply to consumers located in region S_i. In other regions of overlap with other areas, there will (or can) be some decrease in the efficiency (lower productivity, changes in the process parameters, and (or) the quality of products) of consumers located in these areas [1]. The damage Y_i in area S_i can be estimated by the expression

$$Y_i = S_i E_i + S_{ij}\left(E_{ij} - E_i\right) + S_{ijk}\left(E_{ijk} - E_i\right) + \dots .$$

An approximate estimate of the magnitude of total damage Y_Σ based on the probability p_i of failures of generating units in different areas of DG-based power systems will be

$$Y_\Sigma = \sum_{i=1}^{n} p_i Y_i.$$

IV. Assessment of efficiency of DG-based power systems with overlapping service areas

Consider a DG-based power system consisting of two identical generating units, each capable of operating in two conditions: x_1 and x_2.

If both conditions $x_1 \cup x_2$ are possible, then the DG-based power system efficiency is $E = S_2$; if $\bar{x}_1 \cup x_2$ or $x_1 \cup \bar{x}_2$, then $E = S_1$, (at $\bar{x}_i$, $i = 1{,}2$ condition fails) and $S_1 < S_2$; if $\bar{x}_1 \cup \bar{x}_2$, then $E = 0$[7].

The state of the DG-based power system is characterized by a vector with components

$$\left\{x_1^{(1)}x_2^{(1)}x_1^{(2)}x_2^{(2)}\right\}, \quad (3)$$

where the superscript is the generating unit number, and the subscript is a corresponding condition.

Each component (3) takes two values: x_i^jj - power is supplied to consumers, and $\bar{x}_i^j$ – power cannot be supplied.

When $E = 0$ we have:

$$\left\{\bar{x}_1^{(1)}\bar{x}_2^{(1)}\bar{x}_1^{(2)}\bar{x}_2^{(2)}\right\}.$$

When $E = S_1$, there can be two conditions: *a*) arbitrary, but only one component of the vector (3) takes the value x_i^j, and others take the value $\bar{x}_i^j$; *b*) the DG-based power system state is characterized by one of the vectors

$$\left\{\bar{x}_1^{(1)}x_2^{(1)}\bar{x}_1^{(2)}x_2^{(2)}\right\}, \left\{x_1^{(1)}\bar{x}_2^{(1)}x_1^{(2)}\bar{x}_2^{(2)}\right\}. \quad (4)$$

When $E = S_2$, there can also be two conditions: *a*) at least three components of the vector (3) take the value x_i^j, (one generating unit is serviceable); *b*) the DG-based power system state is characterized by one of the vectors

$$\left\{\bar{x}_1^{(1)}x_2^{(1)}x_1^{(2)}\bar{x}_2^{(2)}\right\}, \left\{x_1^{(1)}\bar{x}_2^{(1)}\bar{x}_1^{(2)}x_2^{(2)}\right\}. \quad (5)$$

Comparison of expressions (4) and (5) shows that in both cases the system consists of two generating units operating in one of the possible conditions; the number of impossible conditions is also the same, but efficiency indices are different. The difference is determined by the specific features of the power supply to consumers. According to (4), the DG-based power system appears to be fully operational at the expense of two partially operational generating units.

First of all, the efficiency assessment of the DG-based power systems should be based on fundamental knowledge about their structural, technological, and organizational features; operation principles of the main and control elements; relay protection systems; and automated systems, which constitute them [12, 13]. The order of even a preliminary assessment of the DG-based power system efficiency is as follows:

- obtain the information on the main scheme and operating characteristics and techno-economic parameters of the DG-based power system;
- find out possible tasks of DG-based power system operation;
- investigate the DG-based power system operating conditions in parallel with EPS, independently, and in a combined mode;
- estimate the expected frequency of repetition of tasks and operating conditions of the DG-based power system;
- build a functional diagram of the system;
- divide the DG-based power system into separate areas, and regions;
- select a quantitative measure of the DG-based power system operation quality, which is acceptable for this system;
- calculate the reliability indices of the components characterizing the probability of the state of each component at different time points;
- calculate the probabilities of average (if necessary feasible and/or limiting) states of the DG-based power system based on the probabilities of states of individual components;
- estimate the efficiency indices of possible states of the DG-based power system.
- If for each state of DG-based power system one can estimate an «instant» value of its efficiency (output effect), the efficiency coefficient is determined as an average value of the output effect for all states of the system [2].

V. Examples of a rough assessment of the DG-based power system efficiency

A. Non-overlapping service areas of generating units in the DG-based power system.

Each of the two identical generating units in the DG-based powerystem provides power supply to consumers in its area with probability $p = 0.9$. Assume the availability factor of each generating unit $K_g = 0.95$. For the system to be operational not only at any required time but also during a required interval $t + t_0$, we introduce an interval availability factor.

$$K_g^*(t, t+t_0).$$

In the general case, $p^*(t) \neq p$, since p is the probability of failure-free operation starting with the state of full operability, and $p = 0.9$ is the probability of failure-free operation starting with one of the possible intermediate states. For simplification, we assume that $t \to \infty$ and $p^*(t) = p = 0.9$.

Then
$$K_g^*(t) = K_g p^*(t).$$

In the case of a failure of one of the generating units, the DG-based power system splits into two independent subsystems, each capable of providing only half the load of consumers. The efficiency coefficient of one generating unit is determined as

$$e_{gi}(t) = 0.5K_g p = 0.5 \cdot 0.95 \cdot 0.9 = 0.4275.$$

Consequently, the considered DG-based power system provides the efficiency coefficient equal to $E_\Sigma = 2e_{gi} = 0.855$.

B. Point estimation of the DG-based power system efficiency in the case of the simplest generating units.

The DG-based power supply system consists of two identical power plants (generating units) *Sa* and *Sb* that supply power to consumers with the maximum power consumption $P_\Sigma = 36$ MW. The output of plant *Sa* varies from $P = 0$ to $P = 22$ MW, and that of plant *Sb* – from $P = 14$ to $P = 36$ MW. The power supply areas of these plants are shown in Fig. 7.

It is required to find the probability of supplying the load that occurs at any time in the range $0 \le P \le 36$ MW if the reliability of supplying the necessary power from these

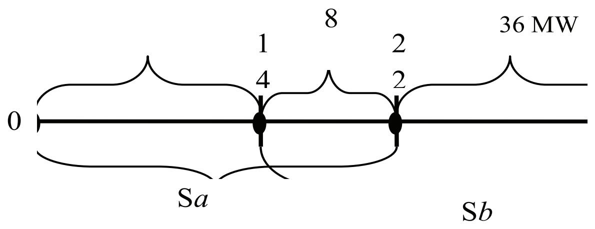

Fig. 7. Areas of power supply from the power plants.

plants at this time point is $R_a = R_b = 0.95$. At he same time, the probability of reliable power supply to the consumers located in the service area of each of the generating units is $R_1 = R_2 = 0.9$, and in the area of simultaneous service of both plants (in an overlapping area), it is

$$\mathcal{P} = 1 - (1 - R_1)^2 = 0.99.$$

Suppose that the consumer load at a given time is P_0 MW. The probability that the DG-based power system will be able to supply it at this time is

$$\mathcal{P}_0 = R_a \cdot R_b = 0.95 \cdot 0.95 \approx 0.9.$$

At the interval from $P = 14$ to $P = 22$ MW (an overlapping area is $P = 8$ MW), the consumer load is provided by both plants, while in the areas from $P = 0$ to $P = 14$ and from $P = 22$ to $P = 36$ MW – by one plant.

The efficiency index E_0 of the DG-based power system state at a given load P_0 MW is determined by the weighted average

$$E_0 = \frac{P_{S_a \cap S_b}}{P_\Sigma}\mathcal{P} + \frac{P_{S_a-(S_a\cap S_b)} + P_{S_b-(S_a\cap S_b)}}{P_\Sigma}\mathcal{P}_0$$
$$= \frac{8}{36}\cdot 0.99 + \frac{14+14}{36}\cdot 0.9 = 0.92.$$

Note that «weight» here is the characteristic of states of the DG-based power system, and not its separate components (generating units). In the same system, the «weight» of a component largely depends on the state for which it is considered. If all components operate but the *i-th* component fails, it is obvious that this failure is accompanied by consequences that differ from the case where this *i-th* component fails after the failure of one component *j (i≠j)* or several components of this system. However, for DG-based power systems, in many cases, a component that is more important in one state of the system proves to be more important in another state of the system as well.

The probability of the system state when one plant *Sa* operates within the load limits $0 < P_a < 22$ MW MW and none of the plants works in the range $22 < P < 36$ MW is

$$\mathcal{P}_a = R_a(1 - R_a) = 0.95 \cdot 0.05) \approx 0.05$$

The efficiency index E_a of the DG-based power system state at a load of P_a MW will be determined as

$$E_a = \frac{22}{36}\cdot 0.9 + \frac{14}{36}\cdot 0 = 0.55.$$

Since in the given example, the states of *Sa* and *Sb* are identical, we obtain the resulting efficiency of the analyzed DG- based power system as follows:

$$E_\Sigma = P_0 E_0 + 2P_a E_a = 0.9 \cdot 0.92 + 2 \cdot 0.05 \cdot 0.55 = 0.883$$

C. Estimation of technical efficiency of the DG-based power system at a given time interval.

The DG-based power system consists of two identical power plants (generating units). If both plants are operational, the load provided by them is P MW. In the case where one of them fails, the value of the provided load is reduced to a value of 0.3P. If two plants fail, the power supply to consumers is completely disrupted. The failures of the generating units are independent events. The probability of failure-free operation of each plant obeys the exponential distribution law

$$p(t) = e^{-\frac{t}{T}} = e^{-\lambda t}.$$

Considering the DG -based power systems of this type, we should take into account the fact that the generating units will not supply the required power to consumers during the shutdown because of preventive maintenance, or due to external factors (weather conditions, if generating units consist of renewable energy sources). However, to simplify the problem, we assume that the distribution remains exponential.

If we take the duration of the calculation period, $\tau = t$ equal to the average failure-free operation period of each plant, i.e., $t = T = 1$ year, the probability of plant failure-free operation will be

$$p = e^{-\frac{t}{T}} = e^{-1} = 0.368.$$

Indices of technical efficiency of DG-based power system states are determined by multiplying the transmitted power by the time of operation:

technical efficiency of DG-based power system operation when both plants are operable during the considered period τ is

$$E_0 = P\tau$$

technical efficiency of DG-based power system operation, when one of the generating units fails at time t_i is

$$E_i(t_i) = 0.3P\tau + 0.7Pt_i \quad t_i < \tau; \quad i = a,b;$$

technical efficiency of DG-based power system operation, when one generating unit fails at time t_i, and the other one – at time t_j is

$$E_{ij}(t_i, t_j) = 0.3Pt_j + 0.7Pt_i \quad t_i < t_j < \tau,.$$

According to the theory presented in [4, 5], the resulting estimation of the efficiency of the analyzed DG-based power system is obtained by the formula:

$$E = p^2 P\tau + 2p\{0.3P\tau(1-p) + 0.7P\tau[1\text{-}p(1+\lambda\tau)]\} +$$
$$+ 2\{0.3P\tau[0.75\text{-}p(1+\lambda\tau) + 0.25p^2(1+2\lambda\tau)] +$$
$$+ 0.7P\tau[0.25 - p + (0.75+0.5\lambda\tau)p^2]\} =$$
$$= 0.368^2 P\tau + 2 \bullet 0.368\{0.3P\tau(1\text{-}0.368) +$$
$$+ 0.7P\tau[1\text{-}0.368(1+1)]\} +$$
$$+ 2\{0.3P\tau[0.75\text{-}0.368(1+1) + 0.25 \bullet 0.368^2(1+2)] +$$
$$+ 0.7P\tau[0.25 - 0.368 + (0.75+0.5)\,0.368^2]\} =$$
$$= (0.135+0.28+0.138)P\tau = 0.553P\tau.$$

The analyzed DG-based power system can be viewed as a system with additive efficiency indices [4, 5] since each generating unit of this system contributes its independent share c_k to the overall output effect. Then the efficiency of the system will be determined by the following expressions

$$E_0 = P\tau\mathcal{P}_0 = P\tau[1-(1-p)^2] =$$
$$= P\tau[1-(1-0.368)^2] = 0.6P\tau;$$
$$E_i(t_i) = 0.3P\tau\mathcal{P}_0 + 0.7Pt_i(1-e^{-\frac{t_i}{\tau}});$$
$$E_{ij}(t_i, t_j) = 0.3Pt_j\left(1-e^{-\frac{t_j}{\tau}}\right) + 0.7Pt_i\left(1-e^{-\frac{t_i}{\tau}}\right);$$
$$E(t) = \sum_{k=1}^{n} E_k c_k = E_0 c_0 + E_i(t_i)c_i$$
$$+ E_{i,j}(t_{i,j})c_{i,j}, \quad \sum_{k=1}^{n} c_k = 1,$$

where c_k is the coefficient of the contribution of each generating unit operating in the DG-based power system.

VI. Conclusion

The development of DG-based power systems puts forward reliability requirements, which differ from conventional ones. Although the reliability of individual components of electric power systems and power supply systems is growing, the pace of this growth is behind the rate of increase in system complexity.

The research has established that the DG-based power systems are characterized by a variable structure, which can be changed randomly, and by overlapping service areas of generating units, which can have various operating conditions. The nature of the functions and many behaviors of the DG-based power system require its high reliability, but numerous components, their connections, and operating conditions can negatively affect the efficiency of the system as a whole. The absence of practical methods for assessing the efficiency and reliability of such systems hinders the improvement in their competitiveness. Therefore, this area of research is essential.

The efficiency of power systems with distributed generation should be estimated by a specialist who is familiar with the entire system, knows the requirements for it, its structure, operating conditions, methods, and tools for control and protection.

References

[1] B. V. Papkov, A. L. Kulikov, "A theory of systems and systems analysis for the electric power industry". M.: Publishing URAIT, 2016. 470 p.

[2] I. A. Ushakov, “A course in the theory of system reliability”. M.: Drofa Publishers, 2008. 239 p.

[3] K. Reinschke, I. A. Ushakov, “System reliability assessment using graphs”. M.: Publishing House “Radio i Svyaz”, 1988. 208 p.

[4] I. A. Ushakov, "Efficiency of the complex system operation”. On the reliability of complex technical sys-tems. M.: Sovetskoye Radio Publisher, 1966. pp. 26–56.

[5] I. A. Ushakov. “Methods of researching the perfor-mance of technical systems”. M.: Znanie Publishers, 1976. 56 p.

[6] E. V. Dzirkal.“Assignment and verification of the reliability requirements of complex products”. M. Pub-lishing House “Radio i Svyaz”, 1981. 176 p.

[7] V. V. Plyamovaty. “On the theory of survival of complex systems”.The main issues of the theory and practice of reliability. M.: Sovetskoye Radio Publishers, 1980. P. 283–292.

[8] B. V. Papkov, A. L. Kulikov, V. L. Osokin, “Prob-lems of the cybersecurity of the electric power industry”. [Library of Electrical Engineering, supplement to the journal "Energy"; Vol. 9 (225)]. M.: NTF “Energopro-gress”, 2017. 96 p.

[9] B. V. Papkov “Vulnerability and resilience of electric power facilities”. Methodological issues of reliability studies of large energy systems: Issue. 68. Research and ensuring the reliability of energy systems. Irkutsk: ESI SB RAS, 2017. pp. 441–452.

[10] Reliability of Technical Systems: A Handbook. Ed. by I.A. Ushakov. M.: Publishing House “Radio i Svyaz”, 1985. 608 p.

[11] Reliability and efficiency in technology: a handbook in 10 v., vol. 5. Design reliability analysis. M.: Mashi-nostroenie Publishers, 1988. 316 p.

[12] Yu. E. Girevich, P. V. Ilyushin. “Features of the calculation of operating conditions in power system areas with distributed generation”. Nizhny Novgorod: NRU RANEPA. 2018. 280 p.

[13] P.V. Ilyushin, A. L. Kulikov. “Automation of the control of normal and emergency conditions of power system areas with distributed generation” Nizhny Novgo-rod: NRU RANEPA. 2019. 364 p.

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A Procedure for Placing Shunt Reactors in High-Voltage Networks and Justification of its Efficiency

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***Abstract* — In recent years, the controlled shunt reactor (CSR), a type of FACTS device, has been widely used to regulate voltage and reactive power flows in the high-voltage electrical network. The selection of location and the determination of the law of CSR control under the stochastically variable operation of high-voltage power transmission lines are associated with numerous technical and economic factors. At the same time, one should take into account such limiting conditions as ease of use, performance, purpose, and location in the system, as well as the time of commissioning. In the proposed procedure, these factors are considered as fuzzy constraints.**

The paper proposes a procedure for CSR placement in the 330 kV electrical network of the "Azerenergy" system for control of reactive power flows, given the mentioned fuzzy constraints. The obtained simulation results demonstrate the advantage of the proposed procedure. The computational experiments confirm the CSR efficiency.

***Index Terms* — Energy systems, FACTS device, power balance, Fuzzy Logic, active and reactive power flow control.**

I. Introduction

Nowadays, the power industries in various countries attach great importance to the creation of controlled or flexible power lines, which are part of Smart Grid with FACTS devices [1-3]. Optimal control of operating conditions of such power systems requires highly efficient means of control of both active and reactive power flows.

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http://dx.doi.org/10.38028/esr.2020.01.0007
Received Month 00, 2020. Revised Month 00, 2020.
Accepted Month 00, 2020. Available online Month 00, 2020.

In recent decades, apart from generators, synchronous and static compensators, switching reactors and capacitor banks, new facilities - controlled shunt reactors (CSR) - have been widely used to regulate voltage and reactive power [4-6]. The economic analysis has shown that without CSR additional power losses are so high that despite the available expensive equipment, the CSR installation pays back in less than 5 years [7,8]. There is still a problem of eliminating excessive reactive power generated under the minimum load conditions in most power grids. The main reason for this excess is that the charging power in 330 kV lines is higher than the losses due to reactive power in them, and this can cause an increase in voltage to a level dangerous for the line insulation.

Conventional methods and means used today to eliminate surplus reactive power are not effective enough and should be replaced by more advanced ones. In this regard, 330 kV CSR is preferable. The relationship between reactive power losses in the networks and their charging power is not constant and varies in a wide range. Therefore, to ensure the reactive power balance, the CSR power must be controlled in a broad range [9].

The selection of power and site for CSR installation, as well as the determination of the law of control, and damping changes in the operation of transmission lines are associated with numerous economic and technical factors. These factors as well as the CSR characteristics affect power losses in the entire power transmission line, the stability of the operation, voltage regulation within the predetermined limits at various values of transmitted power, and overvoltage in individual components of the power transmission line. The selection of CSR should also take into account other factors. These are the convenience of the place for the CSR installation at a given point of the network in terms of operation, performance, technical and economic indices. Therefore, given various uncertain factors for different networks, an acceptable option for the selection and placement of compensating devices is determined.

The authors of [9] show that controlled devices for reactive power compensation, voltage, and power flow regulation should be installed at electrical network facilities if it is necessary to reduce voltage deviations to acceptable levels, increase the transfer capability of power transmission lines (PTL), and reduce losses in electrical networks of power systems. The site, type, and power of the controlled devices should be chosen based on the technical and economic calculations. The economic effect of the use of the controlled devices depends on their cost, damage caused by the accelerated deterioration of equipment due to voltage deviation, cost of losses, and cost of additionally obtained transfer capability of PTL.

Therefore, the determination of an optimal option when selecting compensating facilities in the context of numerous influencing factors and specified practical cases arrives at solving a multi-purpose problem with constraints. However, solving this problem without modern mathematical technologies is extremely complicated.

The issue of CSR placement in high-voltage electrical networks is considered in [10]. Here, the criteria for the decrease in the active power losses and voltage in the network due to the CSR effect are taken as a basis. However, the location of substations in the system, years of operation, scheme, etc. are not taken into account.

A procedure for determining the location of shunt reactors in 330-500 kV electrical networks based on the criteria of short-circuit power, voltage deviation, and reactor power change is given in [11]. Although this procedure provides the necessary methodological support for determining a site for the reactors, it does not allow assessing the level of mistake of not considering the above factors.

A new criterion is proposed in [12] for choosing the location of shunt reactors to improve the transient characteristics of power systems under minimum load conditions, however, the above important factors, affecting the calculation results, are not taken into account.

The focus of the present paper is on the selection and placement of 330 kV controlled shunt reactors based on the studies conducted on a real power system scheme.

II. CSR placement at 330 kV nodes of power system

A special procedure can be used to place the reactor in the power system. To determine the criteria for the selection of the most efficient CSR locations, it is necessary to analyze their impact on two important indices of the power system operation. These indices are the values of absolute and relative reduction in voltage levels at various points of the network before and after the reactor installation, as well as the values of losses in the network. Calculations should be carried out for the minimum load conditions so that the voltage levels at the observed points of the network reach the maximum possible value. Obviously, under these conditions, the reactor power should be maximal. Therefore, during the comparative calculations, the CSR power is assumed to be equal to the reactor rated power for all nodes.

Placement of one CSR at individual substations will affect differently the average voltage level at 330 kV nodes of the power system and the total loss in the networks. The CSR installation at any substation will lower the voltage level both at this substation (mostly) and at other substations. Therefore, the average reduction in voltage can be assumed as the main technical efficiency index of the reactor installation. Another important index is the reduction in power losses in the networks. It is worth noting that with the installation of the single CSR, in contrast to voltage, the power loss can both increase and decrease.

In view of the above-mentioned, the mean absolute δU_{or}, mean relative $\delta \bar{U}_{or}$ voltage reduction, and, accordingly, the absolute δP_{Σ} and relative $\delta \bar{P}_{\Sigma}$ total power loss reduction can be assumed as a special technical efficiency index of the reactor installation. These magnitudes can be determined through multivariate calculations of steady states with the alternate CSR placement at different substations. Moreover, for a comprehensive assessment of

Table 1. Efficiency index values for 330 kv nodes of the power system.

Node No.	Node name	Voltage, kV		Total losses in the network, MW	Absolute and relative decrease in total losses		Average absolute and relative voltage		Efficiency index, E_{ef}
		Bus voltage before CSR connection	Average voltage after CSR connection		MW	%	kV	%	
39	Absheron 330	344.38	334.23	14.5	0.7	4.61	3.60	1.07	4.912
201	Janub PP	346.53	334.66	14.6	0.6	3.94	3.17	0.94	3.701
101	Yashma 330	342.18	333.96	14.9	0.3	1.97	3.87	1.15	2.261
601	Mini HPP	339.44	335.55	14.7	0.5	3.29	2.41	0.71	2.349
651	AzES330	339.23	335.55	14.7	0.5	3.29	2.28	0.68	2.219
400	Goranboy SG	338.76	334.91	14.9	0.3	1.97	2.92	0.86	1.704
333	Agdjabedi330	342.64	333.78	15.0	0.2	1.32	4.05	1.19	1.577
280	Imishli 330	344.27	333.86	15.0	0.2	1.32	3.97	1.18	1.548
801	Khachmaz330	343.43	333.99	15.0	0.2	1.32	3.84	1.14	1.497
411	Shamkir HPP	331.01	336.13	15.4	-0.2	-1.32	1.70	0.50	-0.663
401	Gandja330	329.82	335.79	15.5	-0.3	-1.97	2.04	0.60	-1.190
456	Samukh 330	328.74	335.98	15.6	-0.4	-2.63	1.85	0.55	-1.443
457	GAZ 330	328.28	335.89	15.8	-0.6	-3.95	1.94	0.58	-2.269
502	Agstafa 330	330.89	335.25	15.9	-0.7	-4.61	2.58	0.76	-3.516

technical and economic efficiency of the CSR application, the resulting efficiency index $E_{ef,\Sigma}$ was proposed, which is expressed as follows:

$$E_{ef,\Sigma} = \delta \bar{U}_{or} \cdot \delta \bar{P}_{\Sigma} \tag{1}$$

The value of this index can be used to assess the comparative efficiency of the CSR installation at different points of the network. It should be noted that in the case where the CSR placement has the same effect on the average voltage level (it always declines), it has a double effect on the level of reactor losses.

Thus, in this case, the loss can both increase (useful effect) and decrease (useless effect). The comparison and sequencing of substations according to the $E_{ef,\Sigma}$ index will have an effect at its positive values. In other words, the sites for the CSR installation should be selected among the nodes with $E_{ef,\Sigma} > 0$. In addition, other factors should be taken into account, especially the time of commissioning of substations, the availability of a place for CSR installation, and the possibility of reactive power flows from neighboring power systems.

The values of special and resultant efficiency indices for the 330 kV nodes of the power system (initial loss of 15.2 MW) are given in Table 1. The nodes are arranged in decreasing order of the $E_{ef,\Sigma}$ index values.

As seen in the Table, the $E_{ef,\Sigma}$ value is positive only for 9 nodes of the considered 14, and the sites for reactor installation should be selected between the nodes just with this value $E_{ef,\Sigma} > 0$. In this case, in addition to the condition $E_{ef,\Sigma} > 0$, as noted above, other factors should be taken into account (the periods of commissioning of substations, the availability of sites for the SR installation, the technical capabilities of the switchgear schematic diagram, etc.).

III. Consideration of constraints for CSR placement

The other 5 factors influencing the selection of a site for the CSR installation were taken into account as fuzzy constraints: the substation commissioning time; the substation operation period; the availability of the site for installation; the possibility of an electrical wiring diagram; and the substation location in the system. The Gaussian Z-shape and S-shape membership functions were assumed for linguistic variables [10-13].

The Gaussian membership function is

$$\mu_{ki}(x) = \exp\left(\frac{-(x_i - m_{ki})}{2\sigma_{ki}^{2}}\right), \quad i = \overline{1,n} \quad k = \overline{1,m}$$

where *m* is the coordinate of the maximum;

σ is the concentration ratio.

zmf and *smf* are the membership functions

$$\mu_{ki}(x) = \begin{cases} 1, & x_i \le a_{ki} \\ non-linear\ approximation, a_{ki} < x_i < b_{ki} \\ 0, & x_i \ge b_{ki} \end{cases} \tag{2}$$

where *m* is the coordinate of the maximum; is concentration ratio; *a, d* is a fuzzy set carrier; *b,c* is a fuzzy set kernel, $\mu_{A,i}(x): X_i \to [0,1]$.

For each linguistic variable the fuzzy constraints are introduced on:

the efficiency index:

$$\mu_{EF}(x_1) = \begin{cases} PB, & if \quad x_1 > 3 \\ PS, & if \quad 0 \le x_1 \le 3 \\ N, & if \quad x_1 < 0 \end{cases} \tag{3}$$

the time of commissioning:

$$\mu_{EP}(x_2) = \begin{cases} S, & if \quad 0 < x_2 \le 5 \\ M, & if \quad 2 \le x_2 < 14 \\ B, & if \quad 6 \le x_2 < 18 \\ VB & if \quad x_2 \ge 15 \end{cases} \tag{4}$$

the site for installation:

$$\mu_{IL}(x_3) = \begin{cases} NH, & if \quad x_3 \le -0,4 \\ PN, & if \quad -0,4 < x_3 \le 0,4 \\ N, & if \quad x_3 > 0,40 \end{cases} \tag{5}$$

the schematic diagram of connections:

$$\mu_{ESC}(x_4) = \begin{cases} NH, & if \quad x_4 \le -0,4 \\ PN, & if \quad -0,4 < x_4 \le 0,4 \\ N, & if \quad x_4 > 0,40 \end{cases} \tag{6}$$

the location in the system:

$$\mu_{SL}(x_5) = \begin{cases} SI, & if \quad -1 \le x_5 \le 0 \\ PN, & if \quad 0 < x_5 \le 1 \end{cases} \tag{7}$$

the controlled shunt reactor installation:

$$\mu_{RP}(x_6) = \begin{cases} MP, & if -0,5 \le x_6 \le 0 \\ PP, & if -0,5 < x_3 \le 0,5 \\ P, & if \quad x_3 > 0,5 \end{cases} \tag{8}$$

After the fuzzy implication forms, fuzzy constraints, and membership functions had been determined, the output signals were formed based on the fuzzy approximation between the input and output vectors.

$$\mu_{A,i}(x): X_i \to [0,1].$$

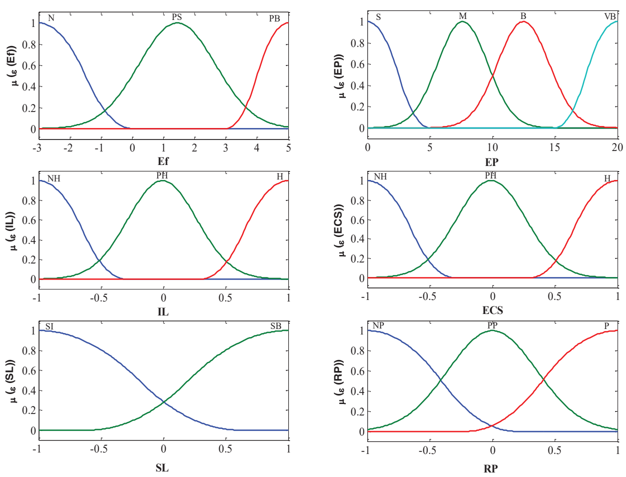


Fig. 1. Membership function of terms of linguistic variables.

Table 2. Terms of linguistic variables, membership functions, and their parameters

Term-subsets	Membership functions	Parameters
	Efficiency index, EI	
Negative (N)	Zmf	[-3 0]
Positive small (PS)	Gaussmf	[1.23 1.44]
Positive big (PB)	Smf	[3 5]
	Commissioning period, EP	
Small(S)	Zmf	[0 5]
Mean (M)	Gaussmf	[2 7.62]
Big (B)	Gaussmf	[2.07 12.47]
Very big (VB)	Smf	[14.97 20]
	Installation sites, IL	
No (NH)	Zmf	[-1 -0.3]
Partially available (PH)	Gaussmf	[0.277 -0.009]
Available (H)	Smf	[0.31]
Connection diagram, ECS		
No (NH)	Zmf	[-1 -0.3]
Partially available (PH)	Gaussmf	[0.277 -0.009]
Available (H)	Smf	[0.31]
Locations in the system, SL		
Backbone. SI	Zmf	[-1 0.607]
Between systems. SB	Smf	[-0.6 1]
	Controlled shunt reactor installation, RP	
Do not install (MP)	Zmf	[-1 0.18]
Partially possible (PP)	Gaussmf	[0.350]
Install (P)	Smf	[-0.2 1]

The membership functions of input and output variables and their terms are shown in Fig.1, and their parameters are given in Table 2.

The fuzzy output mechanism consisting of 65 rules synthesized based on the Mamdani algorithm is shown in Fig.2.

The relationships between the indicated surfaces and output variables (CSR installation node), given the fuzzy constraints, are presented in Fig.4. As can be seen in Fig.4, the red parts of the surfaces describe positive solutions and in each case, they correspond to positive values of efficiency index. In other words, the reactor installation at the indicated nodes leads to both the reduction in voltage at other system-significant nodes and a decrease in active power losses in power transmission networks.

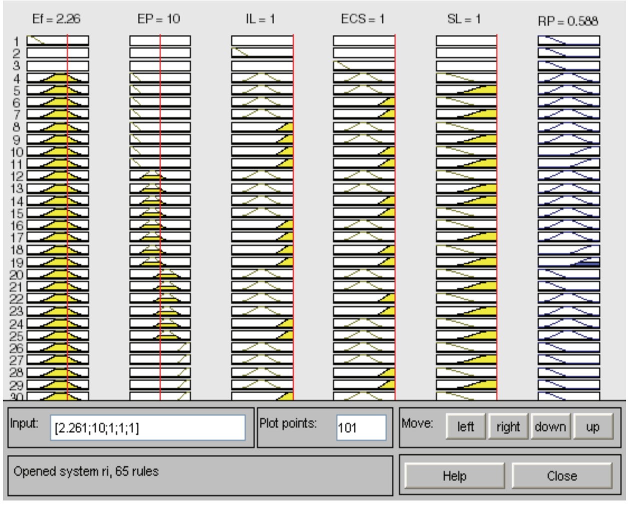


Fig. 3. A decision-making procedure segment.

Table 3 presents the results of adjusting the priority nodes according to this procedure. Calculations were performed based on the ETAP software system considering the fuzzy constraints (3)-(8) [14].

As seen in the Table, the nodes meeting the $E_{ef,\Sigma} < 0$ condition are not considered to be the priority ones and are not taken into account for the CSR installation.

Thus, in terms of these factors, the priority nodes are Goranboy SG, Janub ES, Yashma 330 kV, Imishli SS, and Khachmaz 330 kV. In this case, given the location in the system and the calculation results, we can initially accept the Yashma 330 kV and 330 kV Goranboy SG nodes. The schemes prove efficient and reliable because both nodes meet the condition $E_{ef,\Sigma} > 0$and, also, due to the ability to connect the reactor to busbar at the Yashma 330 kV substation, the availability of a free node in a one-and-a-half breaker arrangement of the 330 kV Goranboy switchgear, and the availability of appropriate sites for the reactor

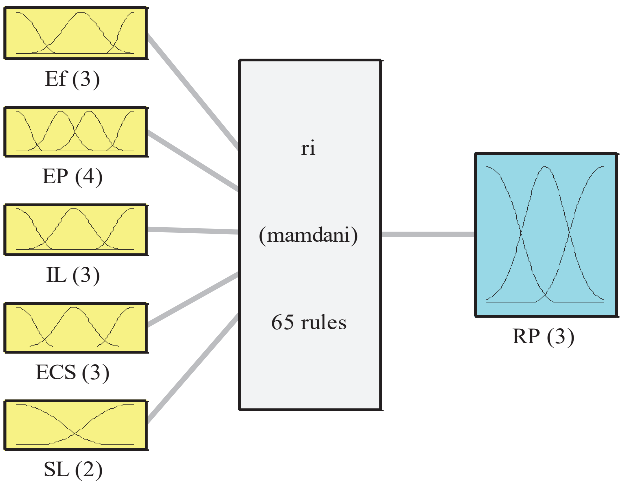


Fig.2. The fuzzy logic output mechanism.

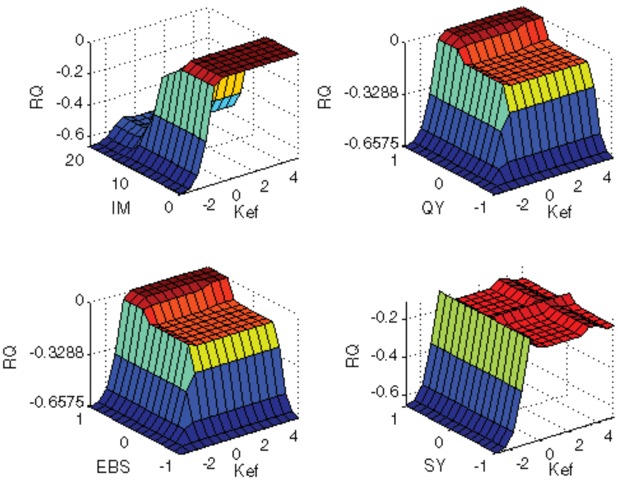


Fig. 4. Fuzzy surface relationships.

Table 3. Efficiency index values for 330 kv nodes.

Node No.	Node name	Voltage, kV		Total losses in the network. MW	Absolute and relative decrease in total losses		Average absolute and relative voltage decrease		Efficiency index E_{ef}	CSR installation
		Bus voltage before CSR connection	Average voltage after CSR connection		MW	%	kV	%		*RP*
400	Goranboy SG	338.76	334.91	14.9	0.3	1.97	2.92	0.86	1.704	0.518
201	Janub PP	346.53	334.66	14.6	0.6	3.94	3.17	0.94	3.701	0.508
101	Yashma 330	342.18	333.96	14.9	0.3	1.97	3.87	1.15	2.261	0.172
280	Imishli 330	344.27	333.86	15.0	0.2	1.32	3.97	1.18	1.548	0.015
801	Khachmaz 330	343.43	333.99	15.0	0.2	1.32	3.84	1.14	1.497	0.014
333	Agdjabedi 330	342.64	333.78	15.0	0.2	1.32	4.05	1.19	1.577	0.013
456	Samukh 330	328.74	335.98	15.6	-0.4	-2.63	1.85	0.55	-1.443	-0.434
411	Shamkir HPP	331.01	336.13	15.4	-0.2	-1.32	1.70	0.50	-0.663	-0.536
601	Mini HPP	339.44	335.55	14.7	0.5	3.29	2.41	0.71	2.349	-0.551
651	AzES 330	339.23	335.55	14.7	0.5	3.29	2.28	0.68	2.219	-0.551
401	Gandja330	329.82	335.79	15.5	-0.3	-1.97	2.04	0.60	-1.190	-0.558
457	GAZ 330	328.28	335.89	15.8	-0.6	-3.95	1.94	0.58	-2.269	-0.631
502	Agstafa 330	330.89	335.25	15.9	-0.7	-4.61	2.58	0.76	-3.516	-0.658
39	Absheron 330	344.38	334.23	14.5	0.7	4.61	3.60	1.07	4.912	-0.658

placement. It should be noted that the 330 kV Yashma substation is very important for Azerbaijan's power system due to its location. The eastern part of Russia's power system is connected to the power system of Azerbaijan via the 330 kV Derbend-Khachmaz PTL, which plays an important role in frequency regulation under extreme conditions. The installation of a controlled shunt reactor at this substation will have a special contribution to the increase in power system stability.

As can be seen in Table 1. the 330 kV Goranboy ES buses and 330 kV Imishli nodes can be considered to be candidates for the CSR installation, as the third node.

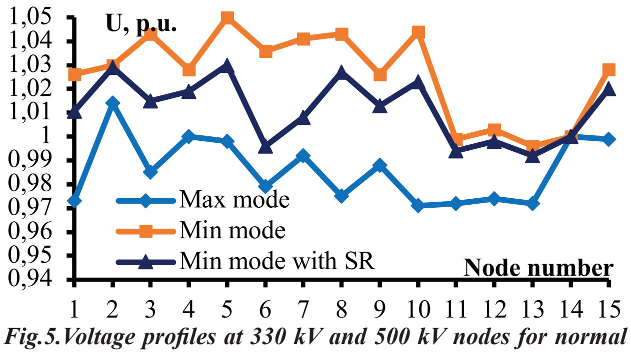


Fig.5. Voltage profiles at 330 kV and 500 kV nodes for normal operating conditions of the power system.

Table 4. Voltage variation limits at 500 kv and 330 kv nodes.

Conditions	Load		Voltage variation interval	
-	P, MW	Q, MVAr	500 kV	330 kV
Maximum	5613.9	3355.2	$(1.0\text{-}1.014)U_{nom}$	$(0.972\text{-}0.999)U_{nom}$
Minimum	1684.2	1006.6	$(1.0\text{-}1.03)U_{nom}$	$(0.996\text{-}1.05)U_{nom}$
Minimum after reactor connection	1684.2	1006.6		$(0.992\text{-}1.03)U_{nom}$

IV. Simulation results

To determine voltage levels at the power system nodes, one should make corresponding calculations for the maximum and minimum load conditions. The voltage profiles of some characteristic 330 kV and 500 kV load nodes based on the calculations performed for the maximum and minimum load conditions in real power system schemes are shown in Fig.5.

It is worth noting that the maximum load conditions of the power system were formed according to the data obtained from the Prospective Development Department of the "AzSRDPPEI" LTD. The minimum load conditions were assumed to be 0.3 Pmax (Pmax is the maximum active load of the power system).

Figure 5 shows that under the maximum load conditions (Py=5613.9 MW, Qt=3355.2 MVAr), the voltage at the 500 kV nodes varies within the (1.0-1.014) Unom interval, at the 330 kV nodes - within the (0.972-0.999) Unom interval. Under the minimum load conditions (Py=1684.2 MW, Qt=1006.6 MVAr), the voltage at the 500 kV nodes varies within the (1.0-1.03) Unom interval, and at the 330 kV nodes - within the (0.996-1.05) Unom interval (Table 4). Thus, the voltage under the maximum and minimum load is within normal limits. At some nodes, the voltage is set to the upper limit.

In the light of the foregoing, the calculation was repeated for the minimum load conditions with a 180 MVAr shunt reactor connected to the 330 kV Goranboy node, and a 100 MVAr reactor connected to the 330 kV Yashma node. As can be seen, with the reactor connection, the voltage profiles in the case of the minimum load conditions improve and change within the range (0.992-1.03) of Unom near the nominal value.

In the next stage, the calculations were made with the modeling of emergency conditions according to the criteria

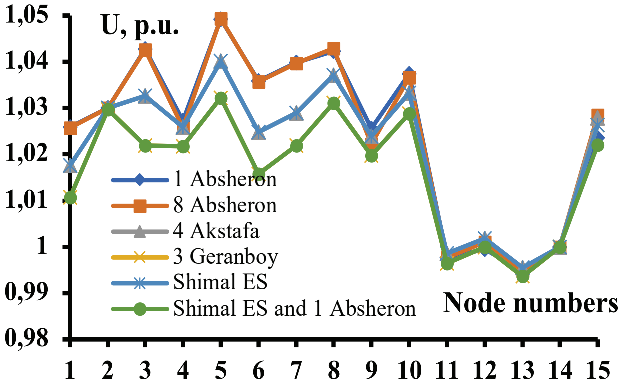


Fig. 6. Voltage profiles for emergency conditions.

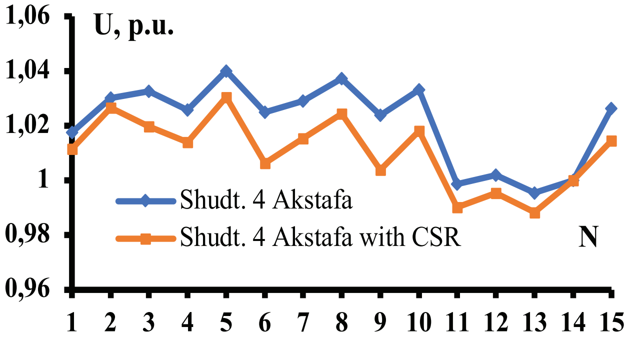


Fig.7. Voltage profiles after CSR connection and disconnection for the case of Agstafa-4 line shutdown

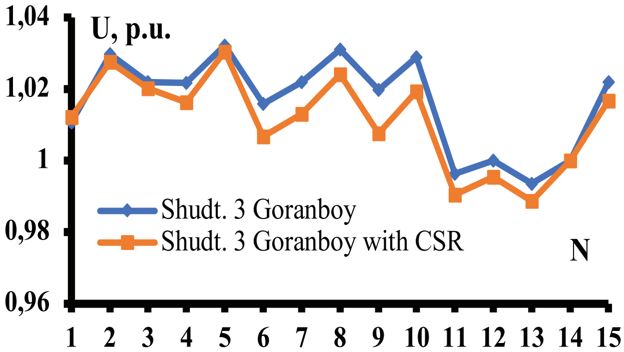


Fig.8. Voltage profiles after CSR connection and disconnection for the case of the Goranboy-3 line shutdown

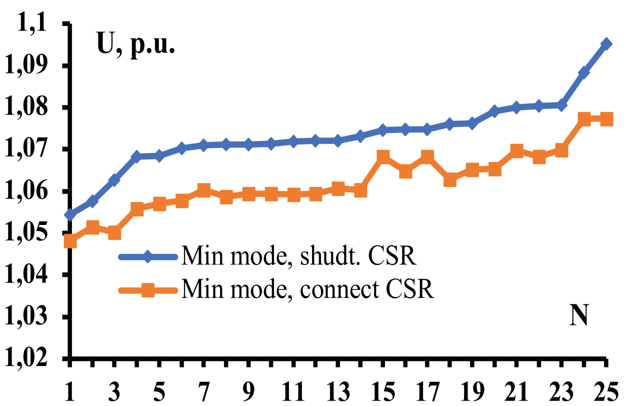


Fig. 9. Voltage profiles at 220 kV nodes of the power system in the cases with and without the 330 kV CSR

N-1 and N-2. We considered the disconnection of lines Absheron-1, Absheron-8, Agstafa-4, Goranboy-3, and Shimal ES according to criterion N-1, and the disconnection of lines Shimal ES and Absheron-1 according to criterion N-2.

Figure 6 shows the voltage profiles at the nodes based on the results of calculations performed according to the N-1 criterion.

As seen in Fig.6, the model calculations for emergency conditions of the power system based on the N-1 criterion indicate the voltage at the nodes within acceptable limits. The voltage at some nodes, for example, at node 5 (Janub ES), after the disconnection of Absheron-8, Agstafa-4, and Goranboy-3 lines reached the upper limit. The same conclusion can be drawn for the Imishli node. Based on this, the calculations were carried out for the case of shunt reactors connected to certain nodes under some of the considered emergency conditions (disconnection of the Agstafa-4 and Goranboy-3 lines).

Figures 7 and 8 show the voltage profiles for the cases of disconnection of Agstafa-4 and Goranboy-3 lines.

Figures 7 and 8 show that with the CSR connection, the voltage profiles relatively improve.

The above results are given for the case of the CSR maximum conditions. Bus voltage curves with the load change at the 220 kV nodes of Yashma SS under the preset power values are presented in Fig.9.

Appropriate calculations for the minimum conditions were performed to study the effect of CSR connected to two 330 kV nodes of the power system on the voltage at 220 kV nodes. According to the calculations, the voltage at 220 kV nodes is within the Unom range (1.054-1.095). In this connection, the placement of compensating devices at the 220 kV nodes was considered.

Lines of the 220 kV nodes generate a charging power of 327.6 MVAr. Voltage profiles obtained using the results of calculations done for the cases of the 330 kV CSR connection and disconnection are presented in Fig.9. As seen in the Figure, the effects of the 330 kV CSR are convex, and the voltage level is within the range set by the power quality standard [15].

V. Results of the reactor efficiency study

The effective operation involves stabilizing voltage in backbone electrical networks by RTU-120000/330 and RTU-180000/330 type shunt reactors, which are installed at 330 kV Yashma SS and 330 kV Goranboy switchgear. The calculations were performed for different load conditions of the power system in a range of reactive power regulation 0 - 100%.

If the shunt reactor is controlled, then the crisp voltage regulation is possible within the range of its voltage regulation with the load change. The calculations were performed to demonstrate it. They confirmed the crisp voltage regulation effect during the load rise in the case of the 100 MVAr CSR placement at the 330 kV Yashma SS

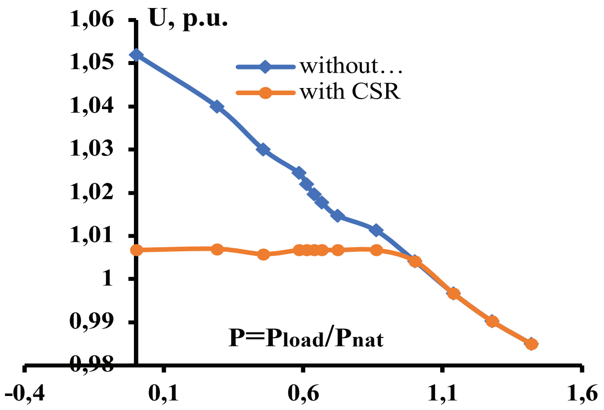


Fig.10. 330 kV bus voltage curves of Yashma SS in the cases with and without CSR

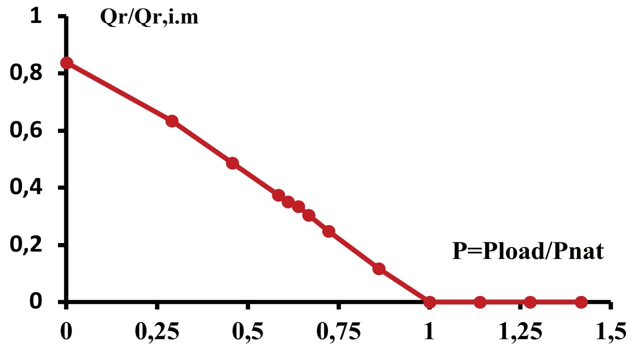
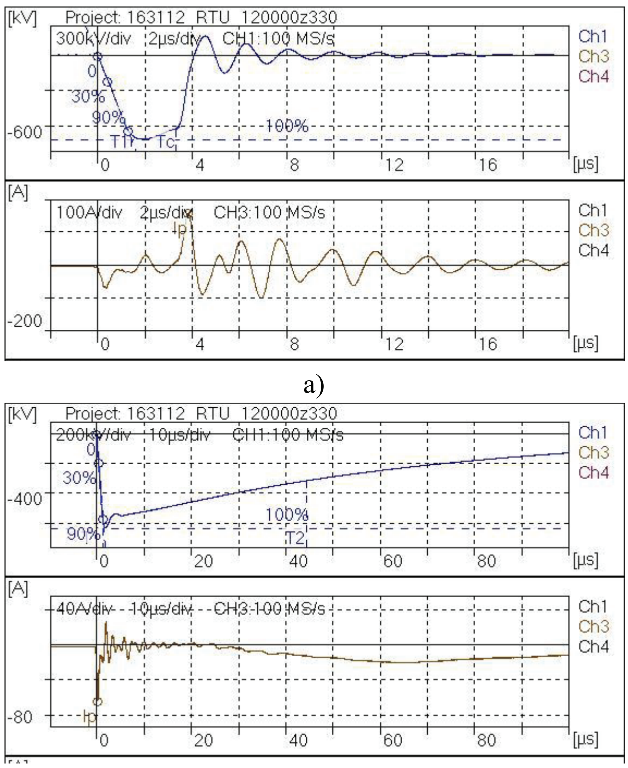


Fig.11. Power curves of the CSR maintaining stable voltage/ load change at 220 kV buses of Yashma SS



a)

b)

Fig.12. CSR's lightning impulse voltage test curves

and voltage curves were constructed on their basis (Fig.10).

As seen in Fig.10, during an increase in active power load in the 0-300 MW range and reactive load in the 0-270 MVAr range at the 220 kV side of the substation, the voltage in the case without CSR reduces up to 0.96 Unom. In the case with CSR, at the expense of crisp regulation (reduction) of its power, the voltage at 330 kV bus, regulated practically crisply, is maintained stable at value 1.002Unom. Only afterward, during subsequent load rises, because the line requires a reactive power, the voltage reduces and, if necessary, in this case, additional regulators should be used. At the same time, Fig.10 shows that if the SR power is not regulated (uncontrolled SR), then bus voltages are not stable and sharply reduce with the load increase.

The power curves of CSR, which stabilizes the voltage with the load increase at 220 kV bus of Yashma SS, are presented in Fig.11. Figures 10 and 11 show that at a load increase, the CSR power crisply regulated in a 100 -0 MVAr range keeps the 330 kV bus voltage stable in allowable limits.

Tests for the reactors of the considered types were performed at manufacturing plants. Reactors' lightning impulse voltage test curves (voltage and current curves) are presented in Figs. 12 a.b.

Fig.12. CSR's lightning impulse voltage test curves

Thus, the above results confirm the efficiency and necessity of CSR for charging power compensation and voltage regulation.

VI. Conclusions

1. The paper proposes a procedure for selecting and placing the controlled shunt reactors at 330 kV nodes with fuzzy constraints to control the reactive power flows in the power system.

2. Based on the developed procedure, the priority nodes for the CSR placement in the Azerenergy system were identified. The calculations of operating conditions with the CSR placed at these nodes were performed. The findings have confirmed a significant improvement in voltage profiles at the nodes.

3. High impulse voltage test curves, which confirm voltage stability at high-voltage buses within the CSR regulation range and define the operating zone, were constructed under laboratory conditions. The performed tests confirmed the reliable operation of the CSR.

References

[1] Tukhvatullin M.M., IvekeyevV.S., Lozhkin I.A., Urmanova F.F. Analysis of modern FACTS devices used for the increase of efficiency of operation of power grids of Russia. Electrotechnical Systems and Complexes. No. 3 (28). 2015, pp.41-46.

[2] Thatarad S., Kiatiyuth K. Load Alleviation in Transmission System by Using Phase Shifting Transformer. 2018 International Electrical Engineering Congress (IEEECON). 7-9 March, 2018, Krabi. Thailand.

[3] Dolgopolov A.G. Bias-controlled shunt reactors. Operation speed issues. News of Electrical Engineering. No.4 (64). 2010.

[4] Bryantsev M.A., Lurie A.I., Spiridonov D.Y. Results of the introduction of bias-controlled shunt reactors in 110-500 kV networks. Electro. No.3. 2006, pp. 25-31.

[5] Bias-controlled electric reactors/ed. by Bryantsev A.M. M.: ZNAK. 2010, p. 288.

[6] Kochkin V.I., Nechaev O. P. Application of static reactive power compensators in electrical networks of power systems and enterprises. M.: ENAS Publishing Group. 2002, p. 248.

[7] Alexandrov G.N. Supervoltage installations and environmental protection. L.: Energoatomizdat. 1989, p. 360.

[8] Controlled bias electric reactors/ ed. by Bryantsev A. M.: ZNAK, 2010, p. 288.

[9] STO 70238424.29.240.99.003-2011. Controlled devices for reactive power compensation, voltage and power flow regulation, conditions of creation. Norms and requirements. Approved and enforced by order of NP "INVEL" dated November 1, 2011, No. 109/4. Moscow. 2011, p. 32.

[10] Hashimov A.M., Guliyev H.B., Babaeva A.R. Selection and placement of compensating devices of the excess reactive power in high-voltage electrical networks. Problems of Power Engineering. No.1. 2019, pp. 3-12.

[11] Nazarova Y.S. Development of a methodology for choosing installation locations for transverse reactive power compensation devices in 330-500 kV networks. Ph.D. thesis, Ivanovo, 2012, p. 24.

[12] Elrazaz Z., Al-Ohaly A.A. Selection of shunt reactor locations to enhance system transient stability at light load operation. Electric Machines & Power Systems. 17:3. pp. 221-231.

[13] Dolgopolov A.G., Condratenko D.V., Ucolov S.V., Postolati V.M. Reactoare controlate shuntate pentru retele electrice. Problemele Energeticii Regionale. 3(17). 2011, pp.1-21.

[14] Hashimov A.M., Guliyev H.B., Babayeva A.R. Managing shunt reactors in accordance to fuzzy controllers for stabilization of voltage in high tension tire-cover. International Journal on Technical and Physical Problems of Engineering (IJTPE). Issue 30, Vol. 9, No. 1, 2017, pp.18-22.

[15] Hashimov A.M., Guliev H.B., Babayeva A.R. Multi-pole fuzzy logic controller to improve the control of shunt reactors//Electricity. No. 6. 2019, pp. 26-32.

[16] Shtovba S.D. Designing fuzzy systems using MATLAB/ Moscow: Hotline-Telecom. 2007, p. 288.

[17] ETAP. Power Station 7.0, User Guide, Volume II, Analysis Modules. Operation Technology. Inc. Registered to ISO 9001. Certification No. A3147. 2002, 3829 p.

[18] Electric power. Electromagnetic compatibility of technical facilities. Electric power quality standards in general-purpose power supply systems: GOST 32144-2013. Moscow: Standardinform. 2014, p.18.

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