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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.

Energy systems research methodology is based on a system approach considering energy objects as systems with complicated structure and external ties, and includes the methods and technologies of system analysis. The system approach is also necessary to address complex energy issues and challenges.

Within this broad multi-disciplinary scope, topics of particular interest include strategic energy systems development at the international, regional, national and local levels; energy supply reliability and security; energy markets, regulations and policy; technological innovations with their impacts and future-oriented transformations of energy systems.

The journal welcomes papers on advances in power engineering and heat supply, energy efficiency and energy saving, renewable energy and clean fossil fuel generation, and other energy technological issues.

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Contents

End-Users Electricity Analysis of a DC-Coupled Hybrid Microgrid by Real-Time Simulation

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***Abstract* — Microgrid has been used to improve the reliability and resilience of existing electric grid, to manage the integration of various renewable energy sources, and to provide the electricity saving benefit by demand side management. It is now emerging from test benches and demonstration sites into commercial applications, which is driven by technological growth. In this paper, a DC-coupled hybrid microgrid is studied and the end-users electricity analysis is discussed. A simulation-based analysis platform is implemented using MATLAB/Simulink and OPAL-RT real-time simulation technology. The investigations involve modelling, and simulation mechanism. The used control strategies are presented, and two different electricity price rates are introduced to calculate the electricity bill for the studied microgrid system operating in different scenarios. Findings demonstrate the benefit of electricity saving provided by the operation of the microgrid system.**

***Index Terms* — microgrid, electricity analysis, MATLAB/Simulink, real-time simulation.**

I. Introduction

Microgrid (MG) is proposed as an application for designing and operating the electric grid in order to achieve a more sustainable and cost-effective energy system while generally providing alternative-energy sources-driven power supply to meet the load demands of grid end-users. Electricity end-users have higher expectancies to seek reliable and lower costs electricity. Thus, the increase in the use of localized energies with the MG solutions is considered to reach this goal. Electricity in a MG system can be collected by different sides, including utility side, end-user side, and MG system side. In the past, some of electricity analysis efforts have been proposed by using time-series simulation tools with simplified (or phasor-type) models [1], [2]. Furthermore, various means such as energy-saving lights and inverter-based electric appliances have also been introduced for electricity saving. To understand the manner of electricity supply and consumption in the MG system, this paper aims to create a simulation-based electricity analysis platform by integrating MATLAB/Simulink and OPAL-RT simulation packages. A power balance electricity management strategy is used for MG electricity control. To observe the performance of purposed simulation platform and to investigate the electricity response of end-users in MG, two simulation scenarios, end-users with and without using load peak shaving mechanism, are implemented. In addition, two different electricity price rates are introduced to calculate the end-users electricity bill.

Overall, the proposed methodologies may be helpful for user demand management and system operation control in MG applications. The rest of this paper is organized as follows. Section 2 describes the configuration of studied MG system and major model characteristics. Section 3 illustrates the various used control strategies and proposed real-time simulation mechanism. Section 4 presents the simulation results obtained using different case scenarios in this work, and conclusions are given in Section 5.

II. Modelling of a DC-coupled hybrid microgrid

Microgrid can be considered as a hybrid electricity system with AC and DC elements. Generally, it refers to an MG system that includes both AC and DC energy sources and loads and depends on how the energy sources and loads are connected to the MG system and how the AC and DC buses are set up. Hybrid AC/DC MG can often be classified into three types: AC-coupled, DC-coupled and AC-DC-coupled [3]. The focus of this research is a DC-coupled one since it is commonly used for low-voltage residential MG application. The investigated DC-coupled hybrid MG (DCHMG) system and its modelling methodologies are presented as follows:

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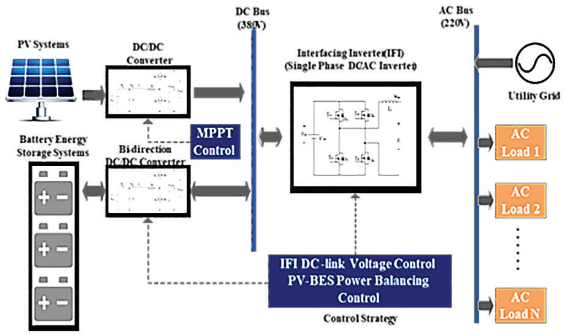


Fig. 1. Configuration of the DCHMG.

A. System Configuration

Figure 1 shows a studied DCHMG system where photovoltaic (PV) generations, including a boost-type DC/DC converter, and battery energy storage (BES) systems, with a bi-direction DC/DC converter, are the main alternative energy sources connected to a common. 380V DC bus. A single-phase interfacing DC/AC inverter (IFI) that provides a bi-directional power flow capability is used to link the DC bus and 220 V AC bus. Furthermore, when multi-IFIs are suited, according to the requirement of power exchange between DC and AC buses, parallel construction of IFIs may be used in order to increase the system rating and reliability. General residential AC loads or variable frequency AC loads can be connected to AC and DC bus, respectively. This structure can be used when DC power sources are major power generations beside utility in the DCHMG, and it is worth noting that if any other alternative energy sources are on AC bus, it is considered to be a different type of MG in the study.

B. Modelling

MATLAB/Simulink is used for modelling and simulation tasks in this study. Completed DCHMG system model is developed in Fig. 2; meanwhile, detailed model for each main electrical component is used in simulations to effectively present the dynamic properties of electricity consumption by the DCHMG end-users. Major models are as follows:

- PV power generations are built by single-diode equivalent circuits that describe the v-i characteristic of the PV arrays and the boost-type DC/DC converters are used to raise the output voltages from PV arrays. Maximum power point tracking (MPPT) control adopts the perturb and observe method [4].
- Lead-acid type generic battery model built-in MATLAB/Simulink is used as the BES [5]. Model parameters like nominal voltage, rated capacity and initial state of charge (SOC) etc. are required for the model inputs. The voltage of lead-acid BES nonlinearly decreases with SOC rate as the battery is in a discharging state; furthermore, lead-acid BES can easily be recharged if the discharge current gives reverse flows in battery model. Temperature effects are ignored in the lebattery model, and it is assumed that the SOC rate of the battery varies with changes in voltage and charging/discharging currents. A non-isolated bi-direction DC/DC converter model is built to achieve a bi-directional power transformation between the DC bus and the battery [6].
- Main end-users in DCHMG system are general single-phase low-voltage residential users. Single-phase full-bridge DC/AC voltage source inverter is modelled to provide AC power supply to each AC end-user [7].

III. Control Strategy and Simulation Mechanism

To carry out the electricity analysis of end-users in MG, the following control strategies and simulation mechanism were used:

A. Power Conversion Control Methods

For the DCHMG operates in either grid-connected or stand-alone modes, the major control and power management objectives are DC-link voltage control, power balancing management between power generations and load demands, and the voltage and frequency controls in AC bus; but, this study focuses only on the DCHMG system operating in a grid-connected mode with the un-dispatched power output. For this operation scenario, let IFI work in DC-link voltage control mode. Then, the DC-link voltage is adjusted to desired values [8]; the PV system should work in a MPPT control state; a constant current control on bi-direction DC/DC converter is required for charging and discharging BESs [9]; and power balancing between all power generations and loads is carried out by [10], [11].

B. Microgrid Electricity Management Strategy

In this study, the purpose of used electricity management strategy is to carry out the power balancing between power generations from each energy source and power consumptions of end-users. It means DCHMG may operate to provide as much electricity as possible to the end-users when alternative energy sources, i.e. PV power and BESs stored power, are sufficient, and then to decrease the power supply from the utility grid (P_{Grid}). To reach the goal, the flowchart in Fig. 4 is implemented to coordinate management of power from *PV* and BES in DCHMG and from utility grid. In Fig. 4, required data of solar irradiance, used to calculate *PV* power (P_{PV}), and end-users' electricity load demand (P_{Load}) are input to simulated DCHMG system for operations. Let us assume the values of P_{PV} and P_{Load}. If $P_{\mathrm{PV}} > P_{Load}$ is false, there are two scenarios that can be met. For $P_{\mathrm{PV}} = 0$, DCHMG end-users' electricity P_{Load} is only supplied by the P_{Grid}. For P_{PV} not equal to 0 and higher than P_{Load}, BES stored power will further be checked. If BESs state of charge (SOC) is less than its low limit of 40 %, then P_{Load} is supplied by the P_{pv} and P_{Grid}, and BESs enter into low-voltage protection stage; if BES SOC is higher than its low limit, P_{Load} is supplied by the limited

P_{PV}, *PBES, and* P_{Grid}. In addition, if $P_{PV} > P_{\mathrm{Load}}$ is true, then BESs over-voltage protection will be checked. For

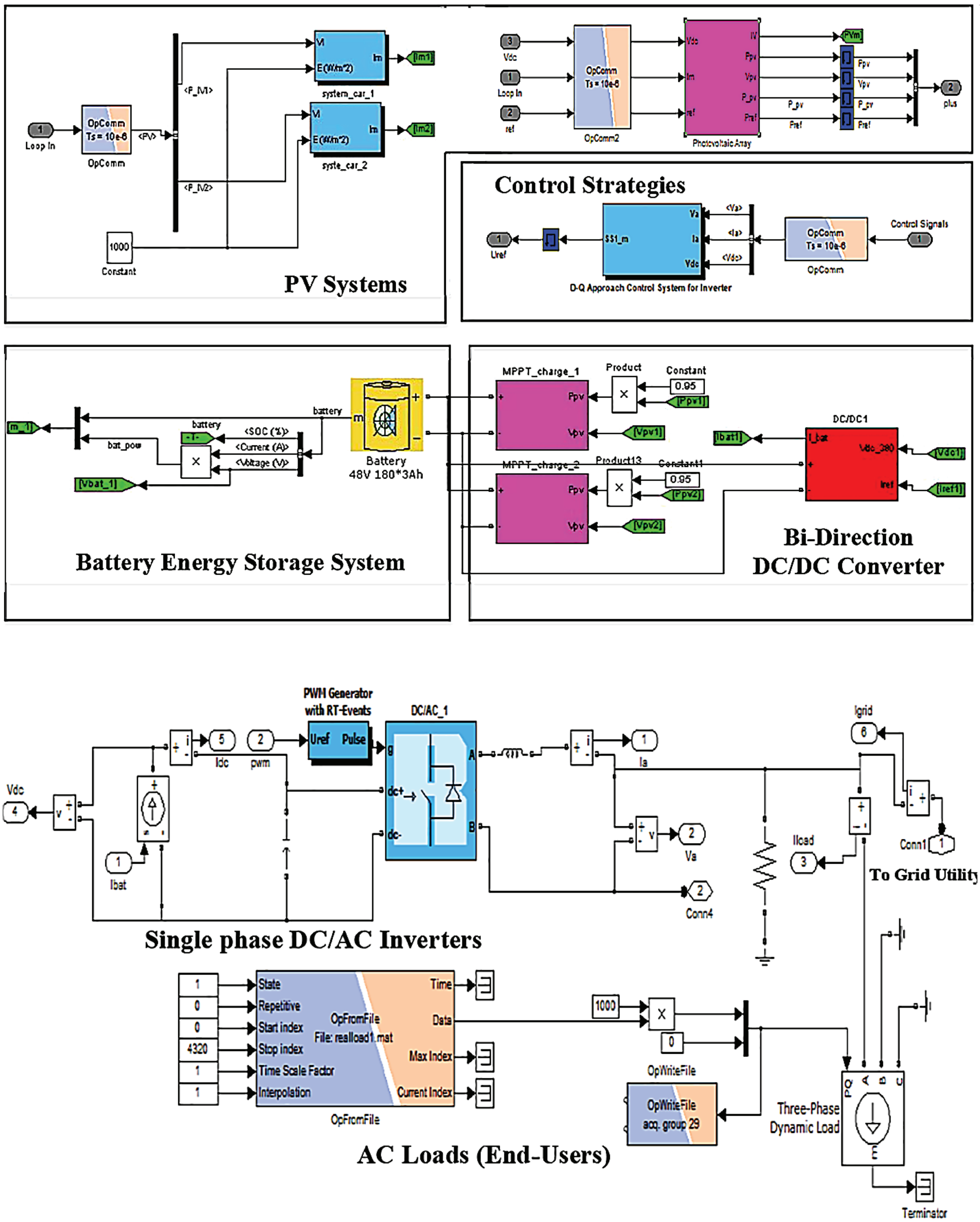


Fig. 2. Modelling of DCHMG

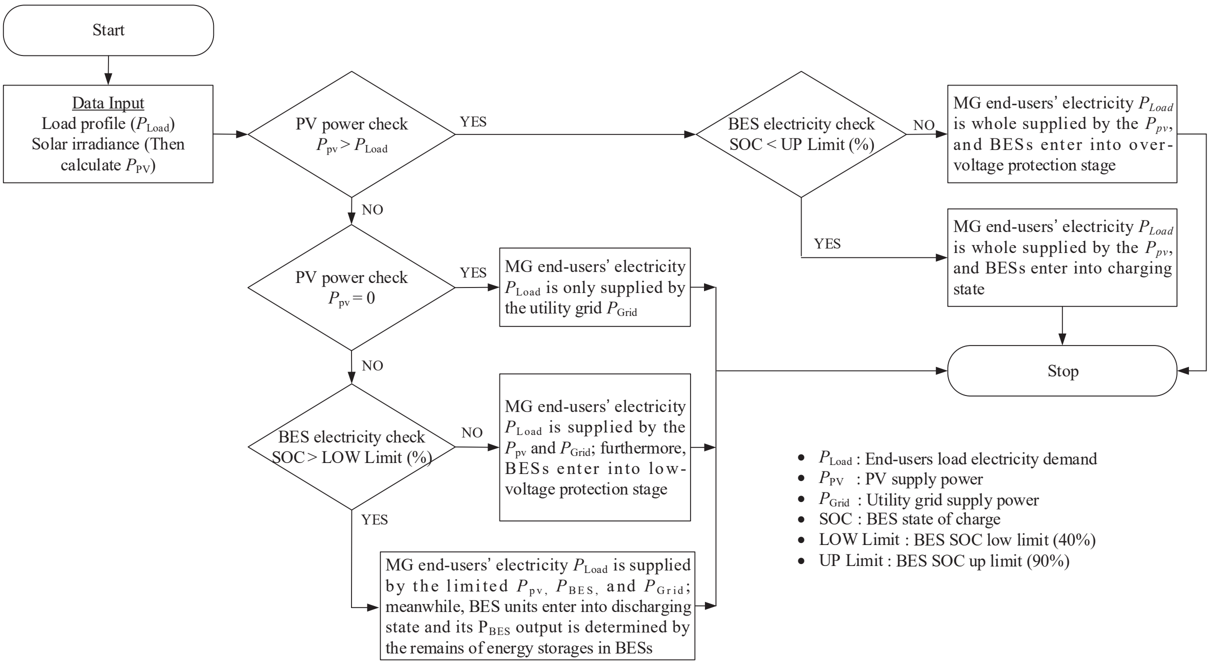


Fig. 3. Microgrid power balance electricity management strategy.

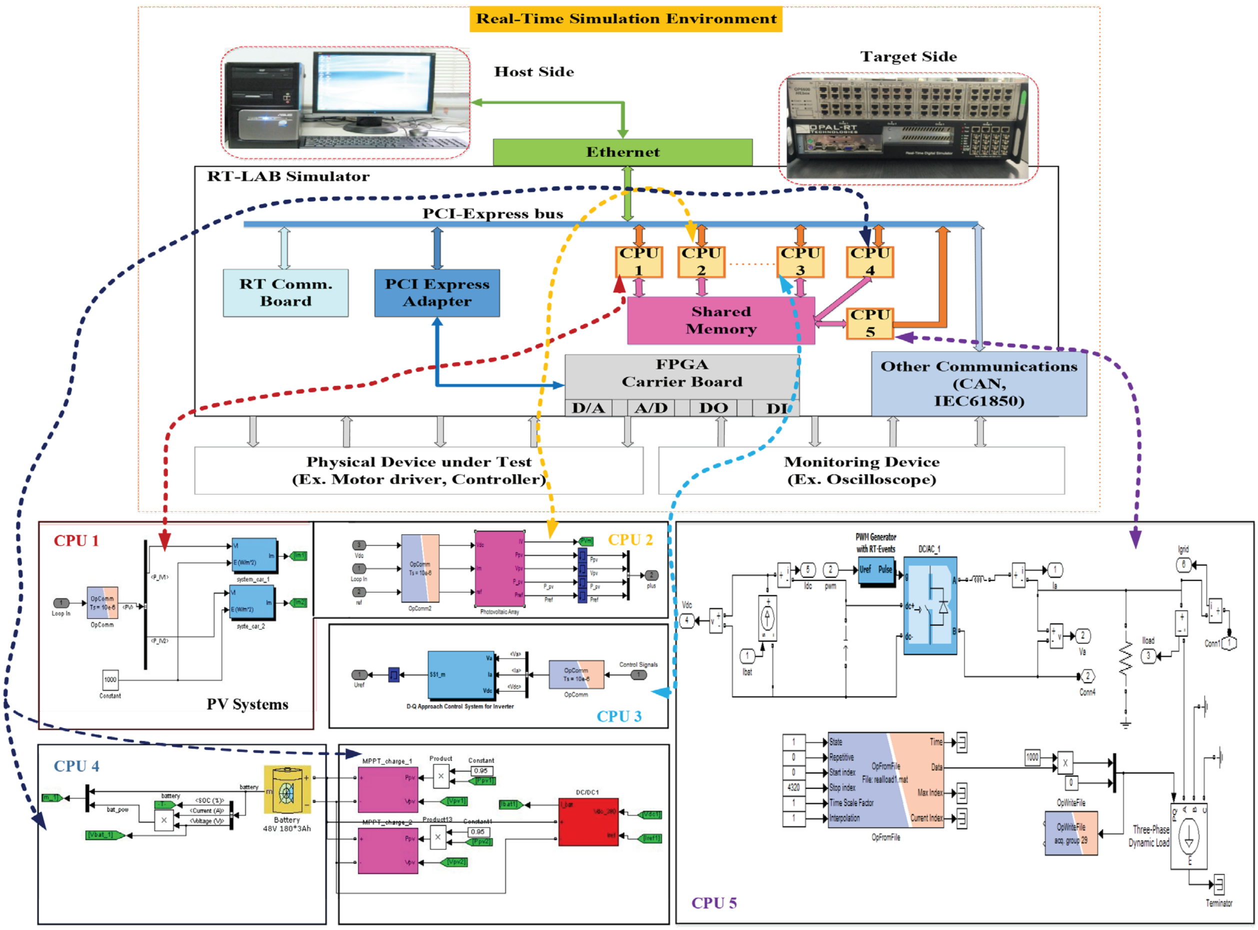
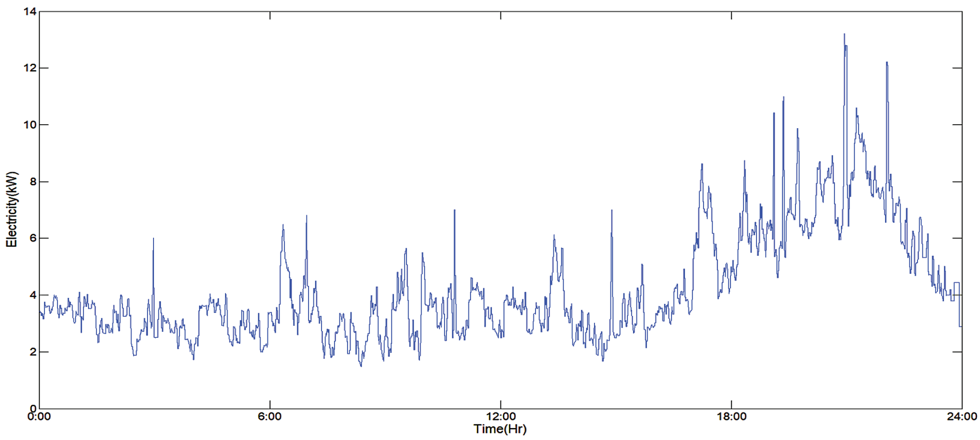


Fig. 4. Configuration of a DCHMG in real-time simulation environment.

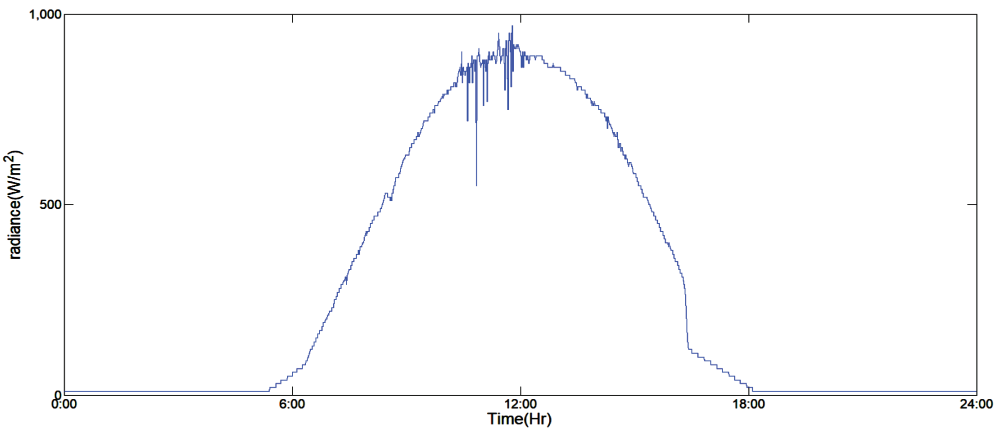
SOC higher than its upper limit of 90%, P_{Load} can be supplied by the P_{PV}, and BESs enter into charging state. For SOC less than upper limit, P_{Load} can be supplied by the P_{PV}, and BESs enter into over-voltage protection stage.C. Simulation Mechanism

OPAL-RT real-time simulation (RTS) technology is adopted in this study for electricity analysis simulations, as shown in Fig. 4 [12]. In RTS environment, the Host side and Target side are two major parts. In the former, a commercial Intel four cores 3.30 GHz CPUs and 8.0 GB RAM personal computer (PC) is used; and in the latter, the OP5600 HIL box with two Intel Xeon six cores 3.46 GHz CPUs and 4.0 GB RAM are used; furthermore, five cluster nodes (CPU cores) are used as well for parallel simulations. Completed DCHMG model in Fig. 2 that relates to the configuration in Fig.1 is divided into five subsystem models and compiled via Real-Time Workshop (RTW) for computations with these models on assigned CPU units. Data exchange between different CPUs is done through the shared memory technique used in PC motherboard that has ultra-low latency property and thus allows the parallel simulation of electric power systems at a small time-step size. The Ethernet protocol with a hundred-Mbps data rate is established to carry out the communication and data conversion between the Host and the Target sides. The operation systems for Host and Target sides are Windows 7.0 and Redhat, respectively. An interfacing software RT-LAB, which builds parallel tasks from the original MATLAB models and runs them on each CPU of the OP5600 HIL box is also required. Overall, the procedures of MG electricity analysis in the study are as follows:

- *Step 1:* to prepare required input data, including assumed system parameters, daily solar irradiance, and initial battery setting as model inputs.
- *Step 2:* to determine the required solar power generation and required battery capacity based on real operation experiences or assumed data and proposed control strategy.
- *Step 3:* to collect load profiles from actual metering infrastructures or assumed data then as end-users load model.
- *Step 4:* to run general simulations in RTS environment and then results of electricity analysis can be produced.



a) Load profile



b) Solar irradiance

Fig. 5 Input data in simulations

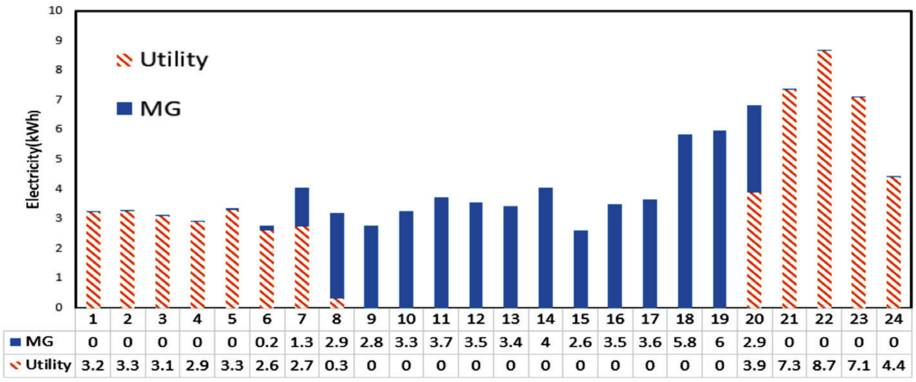


Fig. 6. Simulation results - without peak shaving.

- *Step 5:* to repeat the procedures from Step 2 to Step 4 and set various data/parameters for estimating the performances of the MG system on different test scenarios.

IV. Case study

The following two simulation scenarios are implemented on the DCHMG configuration in Fig. 1:

- DCHMG operation without peak shaving - to observe the electricity status for DCHMG operating on the original load demand profile;
- DCHMG operation with 50 % peak shaving - to observe the electricity status for DCHMG operating on the load demand with 50 % peak shaving.
- Two different electricity price rates are meanwhile substituted into the simulation results for the calculation of electricity bill of end users, and are then compared.

In simulations, the capacities of PV and BESs of about 15 kW and 1.96 kWh are used separately. We used load profile in Fig. 5(a), collected from eight single-phase 110V/60Hz AC residential end-users in DCHMG. Their total consumption of electricity is about 103 kWh in summer days, and used solar irradiance as shown in Fig. 5(b).

A. Without Peak Shaving

Figure 6 shows the simulation results for the eight end- users with a general DCHMG operation, i.e. no peak shaving is implemented. All eight end-users can only receive electricity from the DCHMG during the significant solar irradiance and battery storages durations, i.e. from 7:00 to 20:00. In this simulation scenario, about 49.9 kWh of electricity is supplied by the DCHMG and the remainder of about 53.1 kWh of electricity is provided by the utility grid.

B. With 50 % Peak Shaving

A manual peak shaving is performed to understand the differences between energy-saving solutions for the end-user to get a better effect from electricity saving. Fig. 5(a) demonstrates a peak hour time of the end-users from 18:00 to 23:00. Therefore, the consumed 50 % electricity collected from 19:00 to 22:00 is shaved and transferred to high solar irradiance durations, from 12:00 to 14:00, in this case. Then, the obtained results of electricity analysis are shown in Fig. 7. It is found that the required electricity supply from utility grid can be slightly reduced from 53.1 kWh in Case 1 to 42.0 kWh in this case.

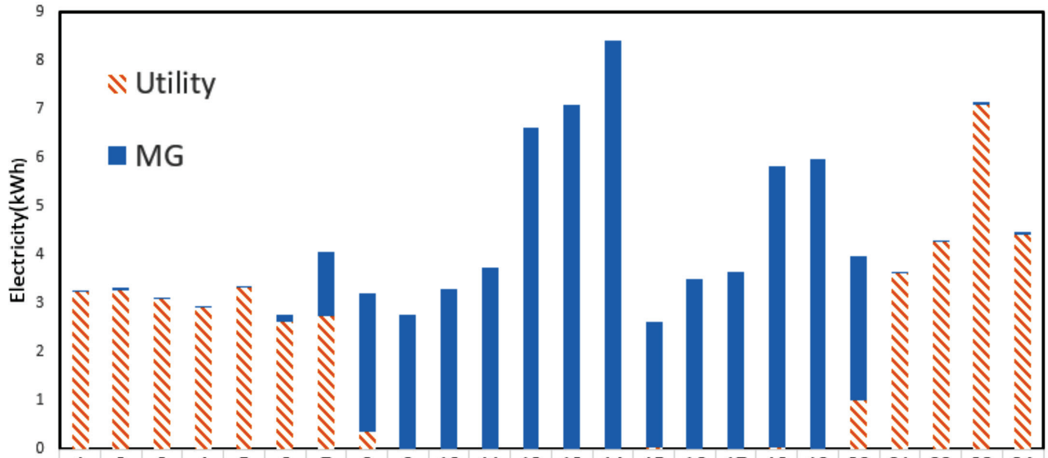
C. Electricity Bill Comparisons of Simulation Results

Two electricity price rules, general electricity price (GEP) and time-of-use electricity price (TOUEP), are used to calculate the total electricity bill for the end-users in previous two cases, separately. Table I shows the prices for GEP, different prices are given for different kilowatt hour segments. TOUEP is given in Table II, this is a two time-segment mechanism, i.e. peak time and off-peak time, and the prices are different for weekdays and weekend days. For weekdays, 4.44 $NTD/kWh and 1.80 $NTD/kWh are used for peak time and off-peak time, respectively; for weekend days, a single price rate of 1.80 $NTD/kWh is used for the whole day electricity; and a price of 0.96 $NTD/kWh is required for the part of the day. The total used electricity exceeds 2000 kWh. Finally, a basis cost of 75 $NTD per month must be included in an electricity bill. Calculations of the total electricity bills of above-mentioned simulation results are summarized in Table III. It is found that without energy-saving measures, the

Table 1. General electricity price for summer season.

Used electricty (kwh)	Price ($NTD/kWh)
<120	1.63
121~330	2.38
331~500	3.52
501~700	4.80
701~1000	5.66
>1001	6.41

1. Supposes there are no losses in load demands and daily used electricity of these 2 months is all the same here. Thus, let 2 months (62 days) electricity be one bill.
2. Calculation of electricity bill: Total bill = {[(120) × 1.63] + [(330 - 120) × 2.38] + [(500 -330) × 3.52] + [(700 - 500) × 4.80] + [(1000 - 700) × 5.66] + [(total used electricity(per bill) - 1000) × 6.41]} × 2



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
MG	0	0	0	0	0	0.2	1.3	2.9	2.8	3.3	3.7	6.6	7.1	8.4	2.6	3.5	3.6	5.8	6	3	0	0	0	0
Utility	3.2	3.3	3.1	2.9	3.3	2.6	2.7	0.3	0	0	0	0	0	0	0	0	0	0	0	1	3.6	4.3	7.1	4.4

Fig. 7. Simulation results with 50% peak shaving.

Table 2. Two-segment time-of-use electricity price for summer season.

Monday to Friday (Weekdays)		Sat. to Sun. (Weekend days)
Peak time ($NTD/kWh)	Off-peak time ($NTD/kWh)	All day ($NTD/kWh)
4.44	1.80	1.80

1. Suppose there are no losses in load demands, one bill includes 2 months; meanwhile, it supposes there are 46 weekdays and 16 weekend days of electricity consumptions. Also, suppose daily used electricity in these 2 months is all the same here.
2. A base cost of 75 $NTD per month is required.
3. Calculation of electricity bill: Total bill = {75 + [(total peak time electricity per day (weekdays) × 4.44) + (total off-peak electricity per day (weekdays) × 1.80)] × (weekdays) + [weekend days × total electricity per day (weekend days) × 1.80] + (total used electricity per bill - 2000) × 0.96} × 2

Table 3. calculation of total electricity price from simulation results.

Items	Electricity Price ($ NTD)	
	General Price (Summer Season)	Time-of-Use Price (Summer Season)
Without peak shaving	15819	7762
With 50% peak shaving	11514	5588

eight end-users in the MG should pay a higher electricity price, 15,819 $NTD for GEP and 7,762 $NTD for TOUEP. Fortunately, it is apparent that the saving on the electricity bill can be met when peak shaving is implemented.

V. Conclusions

Applications of microgrid systems bring various remarkable benefits to help the operations of conventional electric grid infrastructures. Meanwhile, issues for the load demand management and electricity saving are focused on in this study. An effective simulation-based environment by implementing MATLAB/Simulink and OPAL-RT for the electricity analysis in a DC-coupled hybrid microgrid system is thus investigated. Including modelling methodology, real-time simulation mechanism, and power balance control strategy used in this paper are completely discussed. Designed scenarios that consider the options with or without peak shaving are adopted to verify the performance of the proposed electricity analysis simulation system. Finally, the saving benefit on the electricity bill for the end-users in microgird is clearly presented. Proposed microgrid simulation system can be flexibly extended to comply with various microgrid system topologies for other advanced studies. Furthermore, once the “safety” issue is paid more attention in microgrid operation, various microgrid protection means can also be investigated and tested in proposed simulation system by appropriate modelling techniques. These are MG grounding method, protection coordination for switching devices, power conversion-based tripping/disconnecting functionality, etc., which are planned as possible future studies in the context of this paper.

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A Uniform Fault Identification and Location Method of Integrated Energy System

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***Abstract* — With the development of energy coupling devices such as combined cooling/heating and power (CCHP), gas turbines and electricgas transfer device, various energy subsystems are closely coupled into an integrated energy system (IES). Whether it is a power system, a natural gas system or a heating system, a failure in any of them will threaten the safe and reliable operation of the entire IES. Given the lack of unified identification and location of IES faults in existing research, this paper presents a method of unified identification and location of faults using big data analysis. First, the energy hub is used as an energy coupling element, and the dynamic system of natural gas and the model of the regional heating system are established. Combining the analysis of the interaction of other subsystems with other energy systems, the typical features of energy subsystems collected by intelligent terminals are extracted, and the heterogeneous features are spatially and temporally merged into a high dimensional spacetime state detection matrix. The matrix is nonlinearly dimensioned using the Isomap algorithm, and the IES fault identification and location is performed based on the value of the local sparsity coefficient (LSC) value and the node association. The proposed method is validated by the case study.**

***Index Terms* — integrated energy system; interaction; fault identification; fault location; big data**

I. Introduction

With an increase in energy consumption and the distributed generation (DG) accessing to the grid, the limitations of the existing energy system architecture and the contradiction between supply and demand are highlighted. The Energy Internet (EI) can provide a viable solution [1]. EI transforms or even subverts the existing energy industry, to achieve a decentralized mode of production, and promote the large scale development of renewable energy. Integrated energy system (IES) [2,3,4] is an essential physical carrier of EI [5], including electricity, gas, heat (cold) and other energy sources, which is the key to realize the multienergy complementary and cascade utilization of energy.

The safety and stability of the IES determine the normal operation and function of EI. The subsystems of the IES are tightly coupled, if the power grid fails, the state of the coupling unit (energy hub) will be affected, which will lead to a change in the state of the natural gas network and the heat network [6], and vice versa. Therefore, no matter which subsystem fails, this may lead to cascading failures, affect other energy subsystems, and ultimately threaten the economic and reliable operation of IES. Due to differences in physical characteristics, many sophisticated protection methods in a specific system are challenging to be applied to other subsystems. Furthermore, due to the high degree of coupling among subsystems, it is difficult to unify the identification of faults in the power grid, natural gas or heating system.

The papers [79] put forward several methods of distribution network protection, such as using state estimator based parallel synchronous phasor measurements to detect and identify faults in real time. The failure of natural gas pipelines is identified based on the failure probability index [10]. An artificial intelligence method is proposed to detect the leakage fault of the heat network [11]. In [12], an electric-gas IES model is proposed to assess the impact of natural gas regasification terminals on the electricity and gas sector in Colombia. A framework, consisting of the natural gas transient model and power system steadystate model, is established based on AC optimal power flow [13]. In [14], the interaction between electric and heating based on cogeneration technology is simulated to ensure the safety of energy supply. However, these studies focus either on the single energy subsystem,

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or are limited to the study of interaction among systems.

Considering that the IES has the characteristics of rich data and low-value density [1], it is hard for the traditional protection methods to meet the requirements of IES. In view of this, based on the detailed analysis of the fault characteristics of IES, this paper proposes a big data analysis method based on the Isomap algorithm [15] and the local sparse coefficient (LSC) [16].The information uploaded by the terminals is used to integrate the multiple subsystem features into a comprehensive feature. Then, the multidimensional matrix is formed by data preprocessing and data aggregation, and the matrix is nonlinearly dimensioned by Isomap. Finally, the LSC value of each node is calculated based on the LSC method, and the fault of IES is located. This method can break the barriers between networks and unify the identification of faults and areas where they occur in power grid, natural gas and heat grid. The proposed method is validated by the case study.

II. Integrated energy system modeling

A. Natural Gas Network Modeling

The natural gas network is a typical pipeline network with apparent delay [17]. To improve the accuracy of the simulation results, the dynamic equation is used to describe the gas pipes. The following continuity equation and the motion equation [18] are obtained by:

$$\begin{cases} \frac{\partial(\rho\omega)}{\partial x}+\frac{\partial\rho}{\partial t}=0 \\ \frac{\partial(\rho\omega)}{\partial t}+\frac{\partial(\rho\omega^2)}{\partial x}+\frac{\partial p}{\partial x}+g(\rho-\rho_a)\sin\alpha+\frac{\lambda}{d}\frac{\omega^2}{2}\rho=0 \end{cases} \quad (1)$$

where ρ is the gas density, p is the absolute pressure, ω is the velocity of the pipeline flow, x and t are distance and time respectively, g is gravity acceleration, α is the angle between pipe and the horizontal line, d is pipe radius, λ is a coefficient of friction.

The linearized method [19] is adopted to solve the equation. Assuming that the height of the pipeline is unchanged, this means the fourth item in the equation of motion is zero. Furthermore, ignoring the convection item (the second item), this item exists only when the fluid velocity is near the sound velocity. Let M represent A, therefore, the equation can be changed into:

$$\frac{\partial M}{A\partial x}+\frac{\partial\rho}{\partial t}=0 \quad (2)$$

$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial p}{\partial x}+\frac{\lambda}{d}\frac{\omega^2}{2}\rho=0 \quad (3)$$

where M is the mass flow, A is the cross-sectional area of the pipe.

To linearize the model, we use the average gas velocity ϖ [19] to approximate the square item of ω in (3):

$$\frac{\lambda}{d}\frac{\omega^2}{2}\rho=\frac{\lambda\omega}{2d}\varpi\rho \quad (1)$$

Substitute (4) into (3):

$$\frac{\partial M}{A\partial t}+\frac{\partial p}{\partial x}+\frac{\lambda}{d}\frac{\varpi}{2A}M=0 \quad (2)$$

The state equation can link the gas density and pressure. This work adopts a simple relationship (6) between the pressure and density using the sound velocity c

$$p=c^2\rho \quad (6)$$

Finally, the Wendroff difference method is used [20] to approximate (2) and (5), and get the following equations:

$$\rho_{j,t+1}+\rho_{i,t+1}-\rho_{j,t}-\rho_{i,t}+ \frac{\Delta t}{L_{ij}A_{ij}}(M_{j,t+1}-M_{i,t+1}+M_{j,t}-M_{i,t})=0 \quad (7)$$

$$\frac{1}{A_{ij}}(M_{j,t+1}+M_{i,t+1}-M_{j,t}-M_{i,t})+ \frac{\Delta t}{L_{ij}}(p_{j,t+1}-p_{i,t+1}+p_{j,t}-p_{i,t})+ \frac{\lambda\varpi_{ij}\Delta t}{4d_{ij}A_{ij}}(M_{j,t+1}+M_{i,t+1}+M_{j,t}+M_{i,t})=0 \quad (8)$$

B. Heat Network Model

In the heat network [21], the hydraulic conditions are used to describe the distribution of flow and pressure, and thermal conditions are used to describe the distribution of temperature and heat supply.

1) Hydraulic Conditions: The resistance loss in the heat network is calculated by

$$\Delta P=\Delta P_f+\Delta P_j \quad (9)$$

$$\Delta P_f=RL \quad (10)$$

$$R=6.25\times10^{-2}\frac{M^2\lambda_R}{d^5\rho} \quad (11)$$

$$\lambda_R=0.11\times\left(\frac{k}{d}\right)^{0.25} \quad (12)$$

$$\Delta P_j=\alpha RL \quad (13)$$

where ΔP is the loss of the pipeline and ΔP_f is the loss of resistance along the pipe, ΔP_j is the local resistance loss of the pipe, λ_R is the resistance coefficient along the pipeline, D is the inner diameter of the pipeline, ρ is the density of fluid, k is the roughness of the pipeline, R is the average specific friction of the pipeline, L is the pipe length, α is the equivalent coefficient.

The loss of heat dissipation of the pipe is

$$q = \frac{2\pi(t - t_T)}{\frac{1}{\lambda_m}\ln\frac{D_o}{D_i} + \frac{1}{\lambda_T}\ln\frac{4h}{D_i}} \quad (14)$$

where t is the temperature of the pipeline, t_T is the temperature of the soil layer, λ_m is the thermal conductivity of the thermal insulation material, D_O and D_i are the outer diameter and the inner diameter of the insulation layer of the pipeline, respectively, λ_T is the thermal conductivity of the soil, h is the buried depth.

The heat loss in one pipeline is converted to mass flow:

$$M_L = 3.6\times10^{-3}\frac{qL}{C_p\Delta t} \quad (15)$$

where L is the pipeline length, C_p is the specific heat capacity of water, Δt is the temperature difference between the supply and the return water.

2) Thermal Conditions: The relationship between heat power and temperature can be described as:

$$\Phi = C_p M(T_s - T_o) \quad (16)$$

where Φ is the thermal load, T_s is the supply water temperature, T_o is the return water temperature.

Considering the heat loss of the pipe, its temperature calculation formula is:

$$T_{end} = (T_{start} - T_a)e^{\frac{-\lambda_R L}{C_p M}} + T_a \quad (17)$$

where T_{start} and T_{end} represent the water temperature of the incoming and outgoing pipes, and T_a is the ambient temperature.

At the junction point of the heat network pipe, its temperature is calculated by:

$$\left(\sum M_{out}\right)T_{out} = \sum\left(M_{in}T_{in}\right) \quad (18)$$

Considering the network topology, and coupling (16) and (17), we can obtain the following correlation equation for the temperature of the supply and return water:

$$C_s\left(T_s - T_a\right) = b_s \quad (19)$$

$$C_r\left(T_r - T_a\right) = b_r \quad (20)$$

where C_s and C_r are the temperature correlation matrix of supply and return water node respectively, b_s and b_r are constant vectors.

Heating loads are expressed by

$$Q_l = K_l V_l\left(T_{in} - T_{out}\right) \quad (21)$$

where K_l is the volume index and V_l is the volume of room.

C. Energy Hub Modeling

Energy hub [22] is a crucial coupling part of IES, and can be composed of power transformers, microturbine (MT), air conditioners (AC) and heat exchangers (HE). The mathematical model can be expressed as follows:

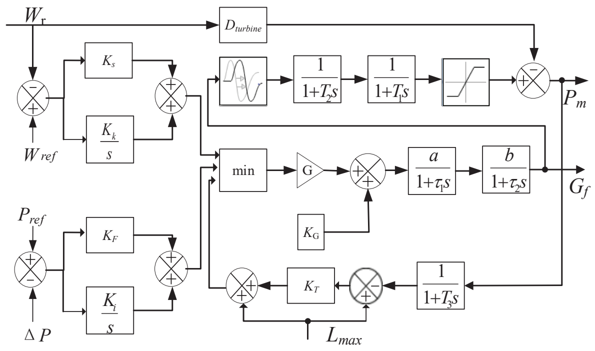


Fig.1. Model of a split shaft gas turbine.

$$\begin{bmatrix} L_e \\ L_h \end{bmatrix} = \begin{bmatrix} (1-\nu_{AC})\eta^{T} & \eta_{ge}^{MT} & 0 \\ \nu_{AC}\eta^{AC} & \eta_{gh}^{MT} & \eta^{HE} \end{bmatrix} \begin{bmatrix} P_e \\ P_g \\ P_h \end{bmatrix} \quad (22)$$

where L_e and L_h respectively represent the electrical load and heat load supplied by the energy hub, ν_{AC} is the partition coefficient, η^T is the efficiency of the transformer, η^{AC} is the energy efficiency ratio of AC, η_{MTge} and η_{MTgh} respectively represent the efficiency of natural gas conversion from MT to electrical and thermal energy, η^{HE} is the efficiency of the HE. P_e, P_g and P_h are the power, natural gas and heat inputs in the energy hub, respectively.

The gas turbine model uses a split shaft gas turbine [23] and increases the fuel supply system, as shown in Fig.1.

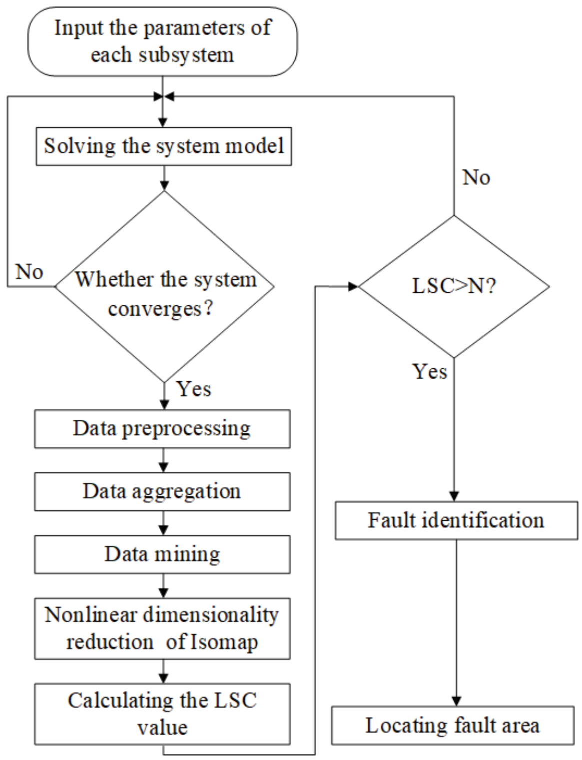


Fig.2. Flowchart of fault location algorithm for IES.

III. Fault location algorithm

A. Algorithm Design

The proposed fault location algorithm for IES has the following four parts: data preprocessing, data aggregation, data mining and fault identification. The flowchart is shown in Fig. 2.

B. Data Preprocessing

1) Select the Characteristics. According to the difference in fault characteristics of each energy subsystem, three-phase current, negative sequence current, zero sequence current, active power and reactive power are selected as characteristics of power system. The pipe pressure and flow are characteristics of the natural gas system. The heat network flow, supply water pressure, supply water temperature, backwater pressure and backwater temperature are the characteristics of heat network.

2) Construct Network Incidence Matrix. To reflect the topological relationship of IES, the nodes in the system are numbered to determine the area constituted by the nodes and adjacent nodes.

3) Standardize the Data. To eliminate the influence of the dimension and the quantity of the characteristic, the standardization of deviations is used:

$$S_j^{i'} = \frac{S_j^i - \min\left(S_j\right)}{\max\left(S_j\right) - \min\left(S_j\right)} \tag{23}$$

where S_j represents a dataset and S_j^i represents a datum in the dataset.

4) Differential Processing. To enhance the difference between the fault node and the normal node, the correlation matrix is used to perform the differential processing of the adjacent nodes and obtain the single-period and single-characteristic matrix C_i:

$$C_i = \left|A^T\right| AT_i \tag{24}$$

where A is the network incidence matrix; and T_i is a column matrix formed by the electrical features data.

C. Data Aggregation

1) Aggregation in Space. In the space, the single-period and single-characteristic matrix C_i is expanded into a single period and multi-characteristics matrix W_i:

$$W_i = [C_1 \quad C_2 \quad \cdots \quad C_n] \tag{25}$$

2) Aggregation in Time. W_i is broadened into a multi-period and multi-characteristics matrix W.

$$W = [W_l \quad W_2 \quad \cdots \quad W_n] \tag{26}$$

D. Data Mining

I) Dimensionality Reduction

Due to the huge amount of data in the high-dimensional matrix W and the information redundancy of the features, all nodes are clustered together in the high-dimensional manifold, resulting in very little difference. Therefore, it is necessary to reduce dimensionality. Here, the nonlinear dimensionality reduction using Isomap is introduced [15]. The traditional Euclidean distance matrix is transformed into a geodetic distance matrix, and then the nodes are connected to form the adjacency graph to simulate the real distance of high-dimensional manifold, and effectively reduce the dimension of the manifold. The calculation process is as follows:

1) Build an adjacency graph G. Based on the Euclidean distance between the adjacent nodes i and j of the matrix W, the nearest m nodes are selected as the sample nodes for each node. The edge of the graph is introduced to connect the adjacent nodes to construct a weighted graph G that can represent the adjacent relationship.

2) Calculate the shortest path of any two nodes on the adjacency graph G to get the geodesic distance matrix D. Its matrix elements are given by :

$$d_{uv} = \left[\min_p \sum_{i=1}^{L-1} d^2(p_i, p_{i+1})\right]^{1/2} \tag{27}$$

where p is a node sequence of length $L \geq 2$ and $p_1=u$, $p_L=v$, $p_i \in D$, (p_i, p_i+1) is the nearest neighbor pair of nodes.

3) The centralization matrix B is calculated by the geodesic distance matrix D, and its element b_{ij} is calculated as follows:

$$\begin{cases} a_{ij} = -\dfrac{1}{2} d_{ij}^2 \\ b_{ij} = a_{ij} - \dfrac{1}{n}\sum_{j=1}^{n} a_{ij} - \dfrac{1}{n}\sum_{i=1}^{n} a_{ij} + \dfrac{1}{n^2}\sum_{i=1}^{n}\sum_{j=1}^{n} a_{ij} \end{cases} \tag{28}$$

4) Solve the two largest eigenvalues of matrix B and their corresponding eigenvectors:

$$\lambda_1 \geq \lambda_2 \geq 0 \tag{29}$$

$$x_{(i)}^{\mathrm{T}} x_{(i)} = \lambda_i, 1 \leq i \leq 2 \tag{30}$$

5) Let $X=[x_{(1)}, x_{(2)}]$ and the matrix X be the representation of the high-dimensional matrix W in two-dimensional space after dimension reduction.

II) Data Outlier Mining.

After the non-linear dimension reduction of the matrix W, the distribution of the nodes can be directly reflected. In order to quantitatively analyze the anomaly of the faulty node, the LSC detection of the matrix X after the dimension reduction needs to be performed.The LSC [16] is an algorithm based on density to detect outliers, which can effectively mine local outliers.The steps are as follows:

1) Find the K-distance $(K_{\mathrm{dist}}(p))$ between each node and its nearest node.

2) Calculate the $N_{k(p)}$ of each node based on the $K_{\mathrm{dist}}(p)$:

$$N_k\left(p\right) = \left\{q \in N / \left\{p\right\} \middle| dist\left(p,q\right) \leq K_{dist}\left(p\right)\right\} \tag{31}$$

where $dist(p,q)$ denotes the distance between nodes p and q, and this node q is the nearest neighbor of node p.

3) Calculate the local sparsity rate of node p:

$$lsr_k(p) = \frac{|N_{k(p)}|}{\sum_{q \in N_{k(p)}} dis(p,q)} \tag{32}$$

where $|N_{k(p)}|$ represents the number of nodes in the $K_{dist}(p)$ of node p, and q represents any node in the $K_{dist}(p)$.The smaller the local sparsity rate of the node, the greater the possibility of reflecting the node anomaly.

4) In the outlier monitoring, the local sparsity rate of the abnormal nodes should be less than the approximate average of all the nodes. In view of this, a threshold can be set to prune the candidate data sets, thus greatly improving the efficiency of the algorithm and reducing the candidate set. The threshold is called a pruning factor *(Pf)*:

$$Pf = \frac{\sum |N_{k(p)}|}{\sum \sum_{q \in N_{k(p)}} dis(p,q)} \tag{33}$$

5) After removing the normal nodes with local sparsity rate greater than or equal to the Pf from the candidate set, the LSC is used to judge whether the node is abnormal. The LSC value of the node is calculated as follows:

$$LSC_k(p) = \frac{\sum_{q \in N_k(p)} \frac{lsr_k(q)}{lsr_k(p)}}{|N_k(p)|} \tag{34}$$

E. Fault Identification

When there is no fault in the IES, all nodes are clustered together in a high-dimensional manifold without outliers, and the LSC values of all nodes are also approximately equal to 1. When there are faults in the system, some nodes will be far away from other nodes and become outliers, and their LSC values will be much greater than 1. This paper sets the LSC threshold of 3 (the threshold setting is usually adjusted depending on the sample). When the LSC value of the node exceeds the setting value 3, it indicates that the fault occurs in the public area where the nodes with the abnormal LSC value are located.

IV. Case Study

As shown in Fig. 3, the IES consists of an improved IEEE 14-node power system, a 16-node natural gas system in the Michigan area of the United States [24], an 11-node heat network [25] and an energy hub. In the power system, node 8 is powered by the energy hub, and node 9 provides power to the energy hub. In a natural gas system, node 19 supplies gas to a split shaft gas turbine. Node 36 provides heat to the energy hub.

I. Interaction Between Faults in an IES

1) Short Circuit Fault of the Power System.

As shown in Fig. 4(a), a single-phase short circuit fault occurred between nodes 4 and 9, resulting in a change in the A-phase current of the line 4-9. In Figs. 4(b) and (c), the flow of natural gas from source nodes 15 and 24 increases correspondingly due to the function of energy hub. The heat network has larger hysteresis of flow and heat transfer. Therefore, the flow rate of heat sink node 31 is affected after a certain time, and the flow rate is slightly higher.

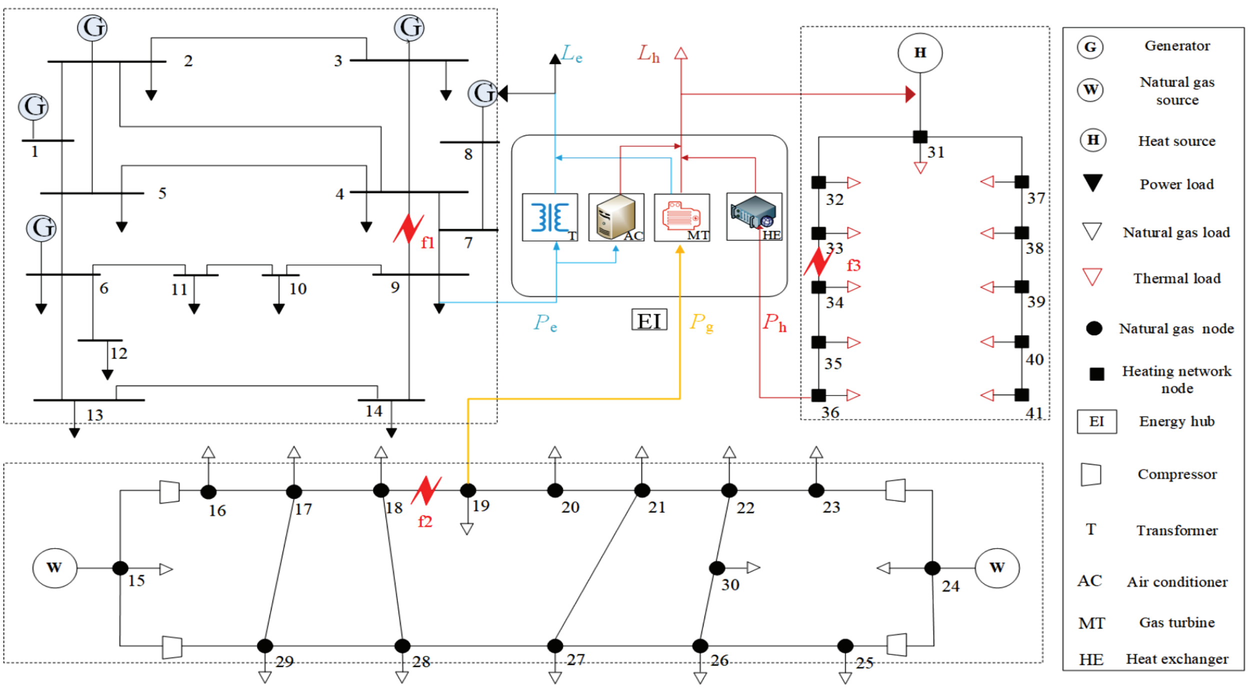
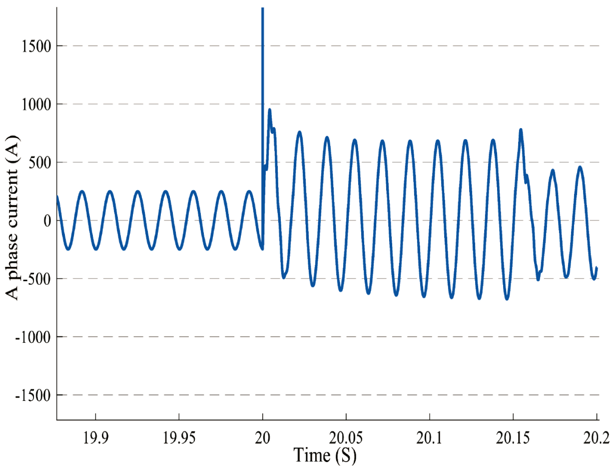
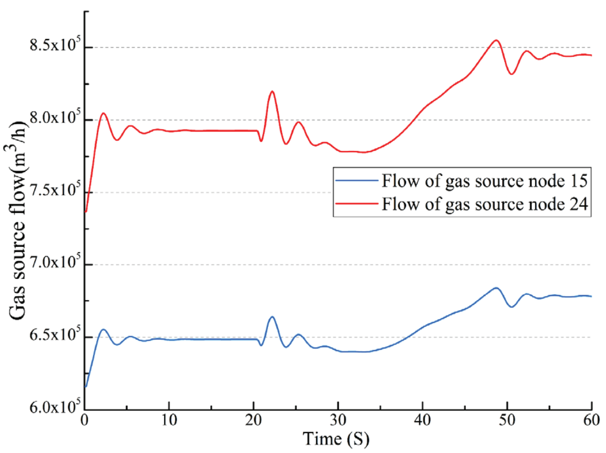


Fig.3. The model of integrated energy system.



a)



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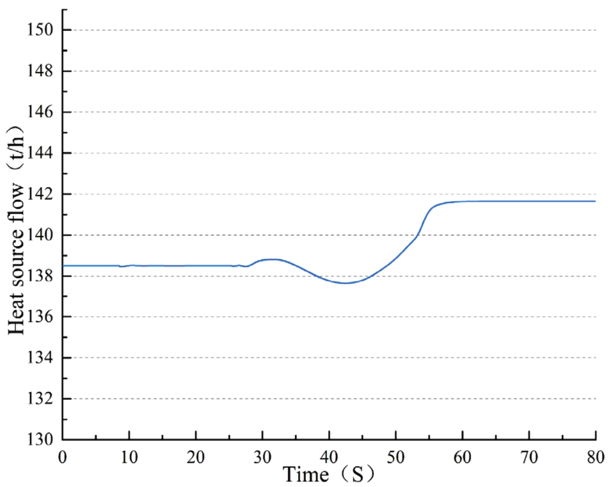

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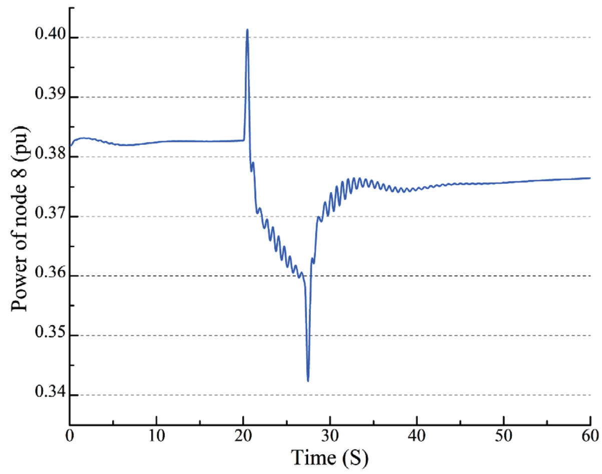
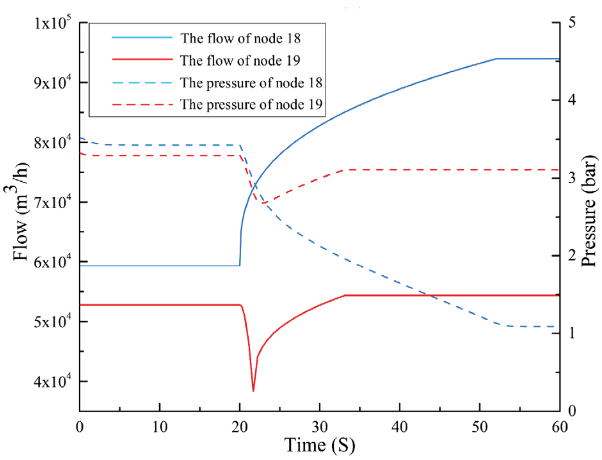
Fig. 4. The typical node waveform for power system fault. (a) A phase current of the line 4-9. (b) Gas source nodes 15 and 24 flows. (c) Heat source node 31 flow.



a)



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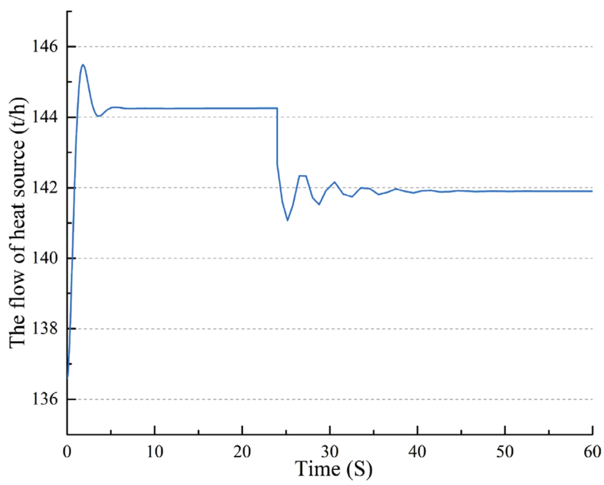

c)

Fig. 5. The typical node waveform for natural gas system fault. (a) The power of synchronous generator node 8. (b) The pressure and flow of nodes 18 and 19. (c) Heat source node 31 flow.

2) Leakage Fault of the Natural Gas Network.

As shown in Fig. 5(b), a pipeline leak fault f2 occurred between nodes 18 and 19. As the natural gas flows from node 18 to node 19, when the leakage occurs, the leak point pressure gradually decreases, resulting in an increase in the flow from node 18. The pressure of node 18 descends to near the standard atmospheric pressure (101.325kPa). After the fault of node 19, the pressure also goes through a period of decline, but after a certain degree of decline, node 24 will supply node 19 again, due to the dual air source. After the fault, the flow rate slightly increases, while the pressure slightly declines. As shown in Figs. 5(a) and 5 (c), due to the natural gas system failure, node 8 in the power system is restarted after short-term power-off. Node 31 of the heat network characteristic also fluctuates.

3) Water Leakage of the Heat Network.

As shown in Fig. 6(c), a water leakage of 20% occurs in the area f3 between nodes 33 and 34. Due to the reduced resistance, the total heat flow will increase. Except for the constant pressure of node 31, the pressure of other supply and return water nodes decrease (the underlined nodes in the Figure are the return water nodes corresponding to the supply water nodes). The pressure drop of nodes 33 and 34 is the largest, and the farther the distance from the leakage point, the smaller the pressure drop. Compared with the normal condition, the hydraulic gradient of the pipe at the upstream of the fault becomes steeper and the hydraulic gradient of the downstream pipe slows down.

As shown in Figs. 6(a) and (b), the output of the gas turbine also increases due to the increased heat network flow. Therefore, the flow of natural gas source is higher. The active output of node 8 is slightly increased.

II. Fault Identification Among IES

1) The Fault of Power System.

As shown in Fig. 7(a), the Isomap analysis shows that nodes 4 and 9 are distributed to the upper right side of the origin of coordinates, leaving the other nodes as outliers, while other nodes gather near the origin of coordinates. In Fig. 7(b), to reduce the error and increase the fault identification rate, this paper adjusts the k value of LSC repeatedly to determine the LSC value of nodes (the setting of k value needs to be adjusted according to the sample).The LSC values of power system nodes 4 and 9 are respectively from 83 to 105 (k = 23 at peak), from 95 to 112 (k = 22 at peak), both far exceed the threshold of 3. However, the LSC values of other nodes are around 1. Therefore, the fault point is in the common area f1 with nodes 4 and 9 that belongs to the power system.

2) The Fault of Natural Gas Network.

As shown in Fig. 8(a), nodes 18 and 19 of the natural gas system deviate from the origin and become the outliers at the lower rate. Node 8 also deviates slightly, while the other nodes still gather near the origin of coordinates.The

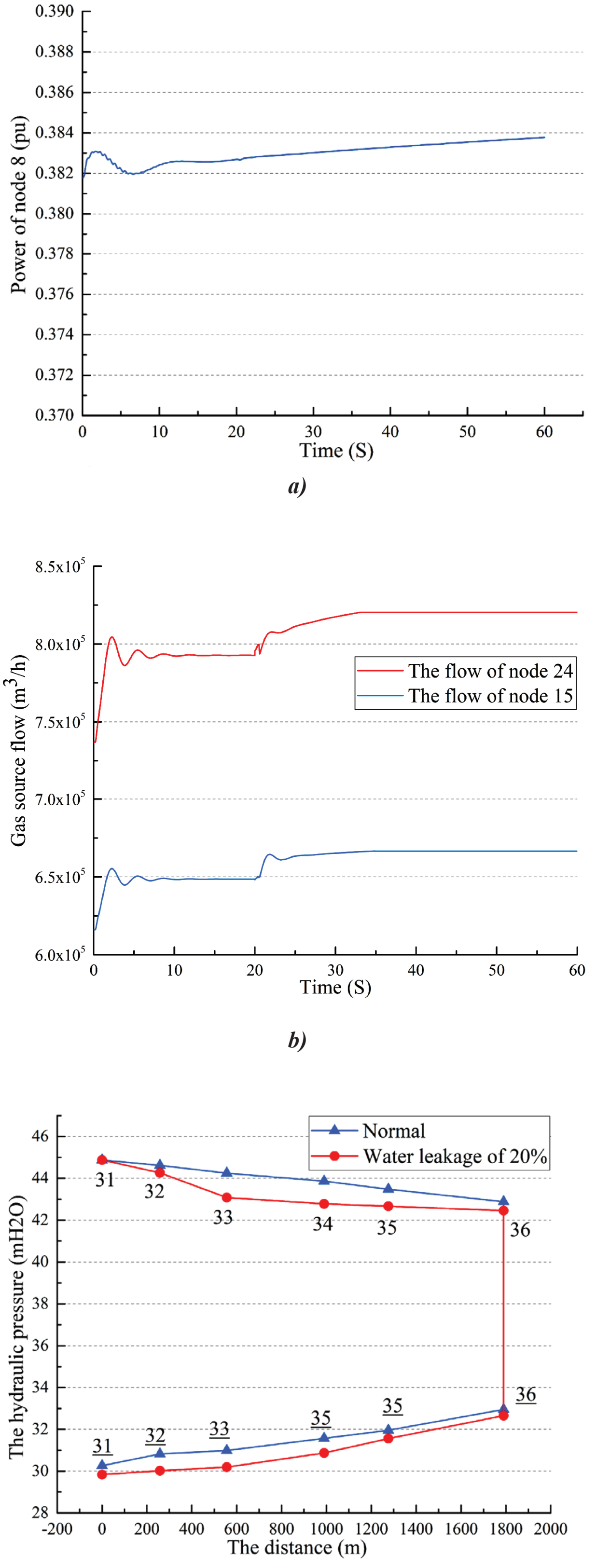

Fig. 6. The typical node waveform for heat network fault. (a) The power of synchronous generator node 8. (b) Gas source nodes 15 and 24 flows. (c) The pressure of the supply and the return water nodes.

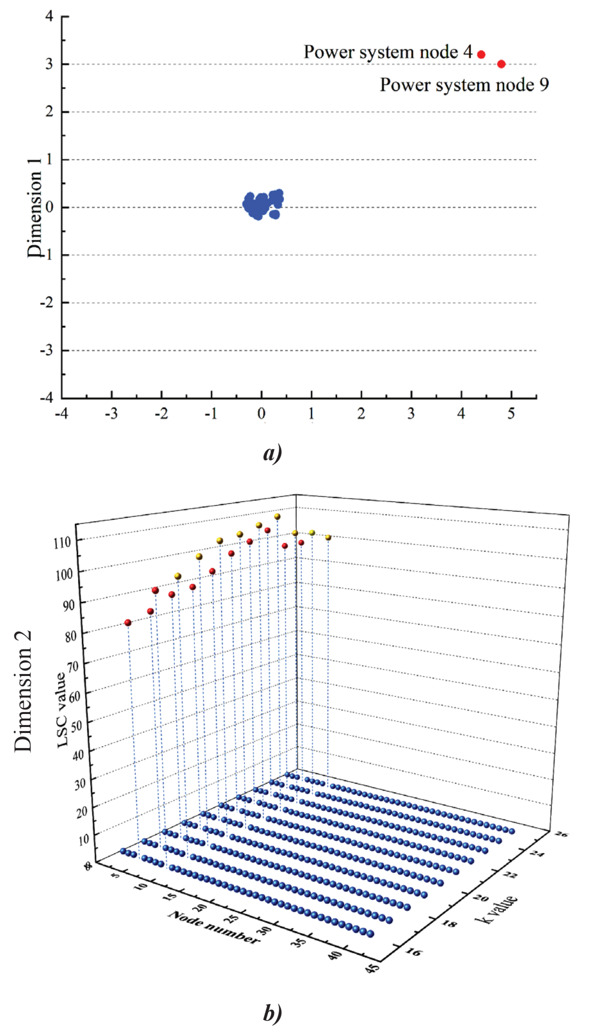

Fig. 7. Fault identification results of the power system fault. (a) Analysis result of the Isomap.(b) Analysis result of LSCat different k values.

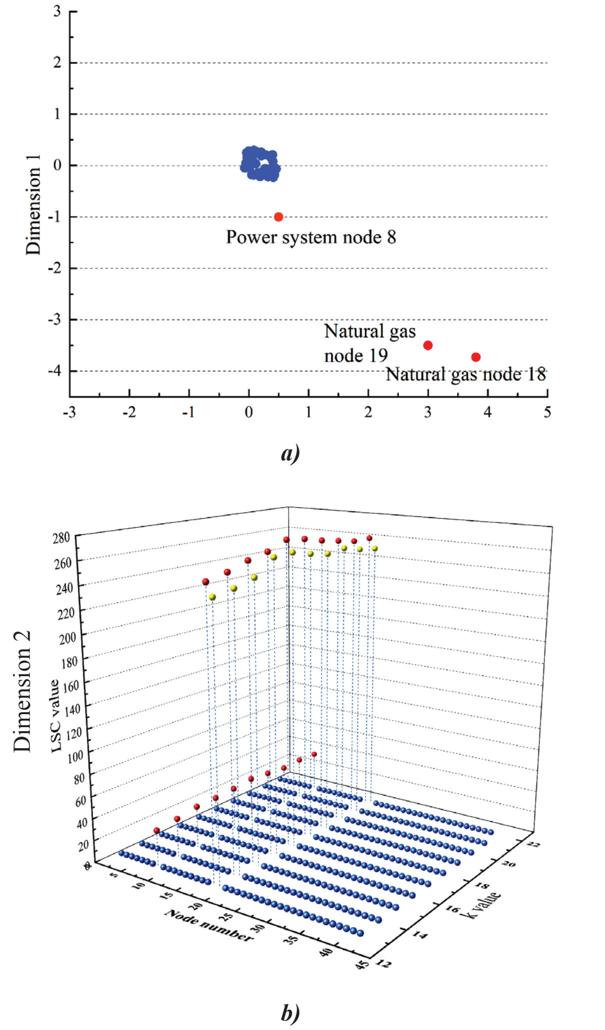

Fig. 8. Fault identification results of the natural gas system fault. (a) Analysis result of the Isomap. (b) Analysis result of LSC at different k values.

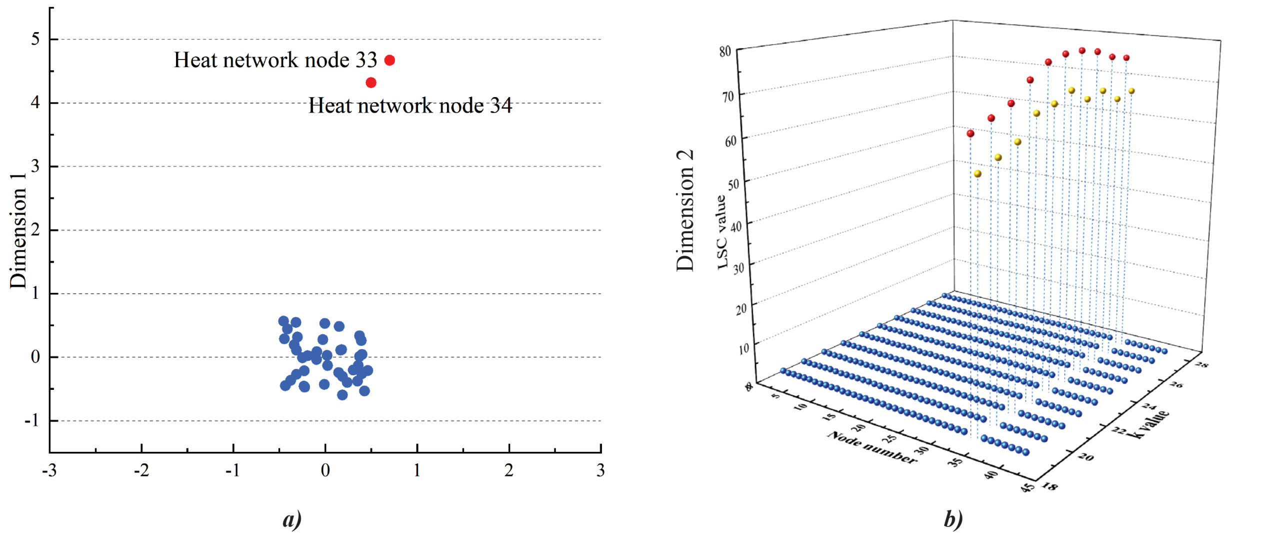

Fig. 9. Fault identification results for the heat network. (a) Analysis result of the Isomap. (b) Analysis result of LSC at different k values.

LSC values of nodes 8, 18 and 19 are from 33 to 41 (k=18 at peak), from 251 to 272 (k=18 at peak), from 240 to 262 (k=17 at peak), respectively. The LSC values of other nodes are all around 1. Node 8 represents an abnormal state of short-time interruption caused by the natural gas system. Combined with the LSC values of nodes 18 and 19, the fault point is in the common area f2 with nodes 18 and 19 that belongs to the natural gas system.

3) The Fault of Heat Network.

As shown in Fig. 9(a), nodes 33 and 34 become outliers, while the other nodes are clustered together. The LSC values of nodes 33, 34 are respectively from 67 to 79 (k = 25 at peak), from 59 to 71 (k = 24 at peak). However, the LSC values of other nodes are around 1.Therefore, the fault point is in the common area f3 with nodes 33 and 34 that belongs to the heat network.

The results of interaction and fault identification in the case studies indicate that the normal nodes converge into clusters, while the abnormal nodes become outliers. Meanwhile, the LSC value of abnormal node is much larger than that of the normal node. According to the above results, when faults occur in different networks, the proposed method can identify the faults of heterogeneous networks belonging to different agents in a unified way, which is conducive and convenient to the improvement of the IES security.

V. Conclusion

This paper proposes a method of state detection and fault location of IES. By combining the characteristics of power, natural gas and heat network, a comprehensive feature quantity is unified, which improves the accuracy of fault identification, and helps to locate the system faults. The interaction caused by a single subsystem after failure is studied, which provides a reference for fault identification and location. Based on the Isomap and LSC methods, the operating data of the IES are used to identify and locate the faults of IES.

This paper considers only one type of faults, therefore the next step of the research will focus on different fault types.

Acknowledgement

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An Analysis of Shortage Minimization Models to Assess Power System Adequacy

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***Abstract* — Continuous changes and expansion of power systems lead to their complexity and aggregation. Therefore, the existing models and software to calculate the reliability of such systems can be inefficient from the standpoint of time, accuracy and adequacy of the results. To obtain objective information, we analyzed some existing power shortage minimization models that are applied to assess the adequacy of a power system. The paper presents the results of the model studies on the availability of a physically incorrect power flow between nodes and two-sided flows. The studies have proven the existence of a set of optimal solutions. The existing approaches considering adequate power flow have been tested. To cope with the described problems we have proposed additional constraints on power flows, and a two-stage method for power flow optimization, which, in the end, enabled the revealed problems to be resolved.**

***Index Terms* — adequacy, optimization methods, power shortage minimization, two-stage power flow model.**

I. Introduction

The electric power industry is a basic industry for successful development and operation of the economy and it must be compatible with the consumer requirements for reliable power supply. Reliability is an important complex property of power systems, which is understood as their capability to supply power to consumers in a required volume and with a required quality. In the stage of power system expansion planning and direct operation, the required reliability level should be assessed and the control actions and plans on commissioning of new system components and retirement of outdated ones should be corrected in due time.

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The current situation is that the expansion of power systems leads to their aggregation, and an increase in the number of generating components and transmission lines. These facts, in turn, dictate the requirements for development of computational tools to assess power system reliability, since the indicated trends decrease the computational efficiency (from the viewpoint of the time spent and validation of calculations) in the process of system reliability assessment because of "outdated" methods and algorithms used.

There are some models and software designed to assess power system adequacy: "MEXICO" model (EDF, France) [1, 2], "SICRET" model (ENEL, Italy) [1, 3], "COMREL" model (University of Saskatchewan, Canada) [4, 5], "POTOK-3" model (SEI SB RAS) [6]. However, these models are not used now. It should be noted that the subject-matter of the adequacy remains topical and is evolving. Therefore, such models and modules as GE "MARS" [7], GridView [8], MARELI [9], PLEXOS [10], ORION / ORION-M model (Komi Research Center) [11], YANTAR model (ESI SB RAS) [12] evolve, gain popularity and are applied to adequacy assessment of present-day power systems.

These products are used to determine the optimal reserve of the power generation and to choose a rational network structure for electric power systems. Therefore, the models represented by the linear minimization problem as well as the highly simplified problem statements distort the assessment results when determining the mathematical expectation of the electrical load undersupply to the system facilities, which, in turn, affects the level of reserve to be determined.

We also consider the "Nadezhnost" software that has been developed recently. This software is intended to study different optimization methods to estimate the efficiency and identify the methods capable of solving the problems with a great number of variables.

Note that the majority of programs apply the algorithm based on the Monte Carlo method [12]. This algorithm includes different mathematical models of optimal power flow with different statements and methods for solving the optimization problems [13]. The algorithm for assessment of power system adequacy is based on the Monte Carlo method and comprises three basic blocks:

1) A probability block for generation of power system

states with components randomly put in or removed from operation.

2) A block for power shortage calculation intended for power shortage minimization in each generated system state.

3) A block for calculation of power system reliability indices, which is designed to process and analyze all the stored information (the result of work of two previous blocks) and calculate such adequacy indices as the probability of failure-free (shortage-free) operation, the mathematical expectation of power shortage in power systems, the mathematical expectation of power undersupply, etc.

The core of the considered algorithm is the second block responsible for the calculation of power shortage in different power system states. The quality of the results, which implies the calculation speed and accuracy, the capability to solve the problems with an increasing number of variables, depends on the applied optimization method and the model correctness. In the end, the minimal difficulties or delays in calculations increase the time spent on solving the whole problem. Thus, the goal is to solve the power shortage minimization problem as fast as possible within a short space of time.

The research is mainly focused on an analysis of power shortage minimization model, which takes into consideration quadratic power losses, conformity of the model to real physical processes, application of different optimization approaches and methods, namely, a combination of the penalty function method and the gradient descent method.

II. Problem statement

The problem of power shortage minimization is formulated as follows:

Determine an optimal power flow in a power system for the known values of generating capacities in operation, the required levels of consumer loads, the transfer capabilities of tie lines in a power system and the factors of power losses in the system tie lines [12]. There exist several types of power shortage minimization models, and this paper deals with the models applied. The linear statement of the problem is presented below.

Mathematically, the problem is formulated as follows:

$$\sum_{i=1}^{n}(\grave{y}_i - y_i) \rightarrow \min_{y}, \quad (1)$$

subject to the balance constraints:

$$x_i - y_i + \sum_{j=1}^{n}(1 - a_{ji})z_{ji} - \sum_{j=1}^{n} z_{ij} = 0, \quad (2)$$
$$i = 1, \dots, n, i \neq j,$$

and to the constraints on optimized variables:

$$0 \leq y_i \leq \grave{y}_i, i = 1, \dots, n, , \quad (3)$$

$$0 \leq x_i \leq \grave{x}_i, i = 1, \dots, n, , \quad (4)$$

$$0 \leq z_{ij} \leq \grave{z}_{ij}, i = 1, \dots, n, j = 1, \dots, n, i \neq j , \quad (5)$$

where: x_i the usable capacity (MW) at node *i*, $\grave{x}_i$ is the available generating capacity (MW) at node i, y_i is the load to be supplied at node i (MW), $\grave{y}_i$ is the load value at node *i* (MW), z_{ij} is the power flow from node *i* to node *j* (MW), $\grave{z}_{ij}$ is the transfer capability of the transmission line between nodes *i* and *j* (MW), a_{ji} is the given positive coefficients of specific losses of power when transmitted from node *j* to node *i*, $j \neq i$, $i=1,\dots,n$, $j=1,\dots,n$.

Model (1-6) is a common model of power flow for the adequacy assessment, which is solved by minimizing power shortage and is a transportation problem. The presented optimization problem is solved basically using the simplex method and the dual simplex method in their different variations, for the reason of the model simplicity. However, in [12] the authors present a valid conclusion that the model, where the power losses depend on the squared transmitted power, is a more adequate model. For this purpose, model (1-5) includes the modified balance equations, in which the constraints of type (2) are replaced with the following constraints:

$$x_i - y_i + \sum_{j=1}^{n}(1 - a_{ji}z_{ji})z_{ji} - \sum_{j=1}^{n} z_{ij} = 0, \quad (6)$$
$$i = 1, \dots, n, i \neq j.$$

Thus, the stated problem can be presented in two forms – the problem of linear and nonlinear programming. The problem form strictly depends on the applied balance constraints in formulas (2), (6). The linear programming problem is solved if the balance constraints contain equations only with the linear losses. The nonlinear programming problem is solved, when the balance constraints contain equations with the quadratic losses. The latter can be solved by different methods of constrained and unconstrained optimization. However, this problem cannot be solved by the standard methods of unconstrained optimization because of available different equality and inequality constraints. For this purpose, the objective function and all constraints should be presented in the form of the common objective function. For example, in the YANTAR [12] software, the problem in the linear statement was solved by the Lagrange method and various modifications of the interior point method. It is worthwhile to note that the problem is solved for the long-term power

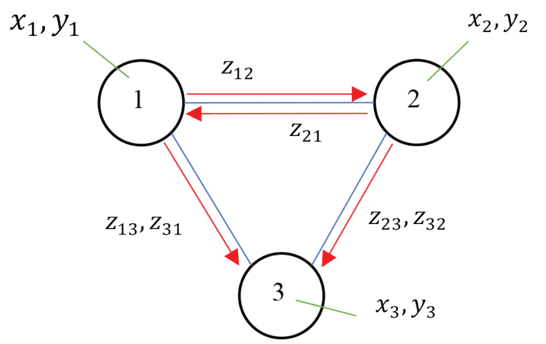

Fig. 1. Schematic representation of power flow.

system expansion planning, it uses certain equivalent methods and there is also uncertain information that can be used to solve it.

In the process of studies, we validated models (1-5) and (1), (3-6) using the test scheme (TS1). TS1 is a system (Fig. 1) consisting of three nodes and three tie lines with a ring topology. We applied a combination of the penalty function method and the gradient descent method (PFGD) as the optimization method. Based on the validation results, we obtained a solution where the optimized variables for flows z_{12} and z_{21} had positive values, which indicates a nonconformity of models (1-5) and (1), (3-6) to physical processes.

The obtained solution contained the data on the availability of involved flows (Table 1), whose power was distributed in both directions simultaneously, which contradicts the physical reality because each transmission line in each specific state can operate only in one direction. This fact indicates that only one variable for flows z_{12} or z_{21} responsible for one tie line can take a nonzero value.

Table 1. Test results, model (1) – (5), (2) – (6).

			PFGD (1)-(5)	PFGD (2)-(6)
$\grave{x}_1$	158	x_1	103,94	103,97
$\grave{x}_2$	109	x_2	105,21	105,22
$\grave{x}_3$	83	x_3	83	83
$\grave{y}_1$	91	y_1	91	91
$\grave{y}_2$	98	y_2	98	98
$\grave{y}_3$	201	y_3	102	102
$\grave{z}_{12}$	10	z_{12}	3,94	3,96
$\grave{z}_{21}$	10	z_{21}	1	1.02
$\grave{z}_{13}$	10	z_{13}	10	10
$\grave{z}_{31}$	10	z_{31}	0	0
$\grave{z}_{23}$	10	z_{23}	10	10
$\grave{z}_{32}$	10	z_{32}	0	0
		a	0,05	0,05

This situation was eliminated by the formulation of an additional constraint on power flows:

$$z_{ji}\, z_{ij}=0, i=1,\dots,n, j=1,\dots,n, i\neq j\ , \tag{7}$$

Thus, constraint (7) transforms the considered problem into a correct one from the standpoint of modeling of power flows between the nodes and alters models (1-5) and (1), (3-6) into correct ones from the standpoint of physics.

III. Models of power shortage minimization in power systems

Models (1-5), (7) and (1), (3-7) are two mathematical models of power shortage minimization in power systems, which are used for adequacy assessment. Model (1-5), (7) takes into account linear power losses, and model (1), (3-7) – quadratic power losses. However, the presented models have some downsides that have been eliminated for a long time by the modification of these models and approaches to solving the above problems.

The incorrect power flow is one of such downsides.

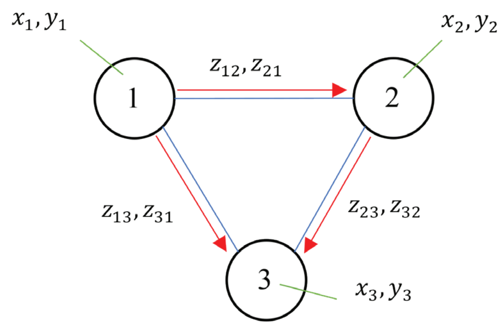

Fig. 2. An illustrative example of an incorrect power flow.

Thus, validation of models (1-5), (7) and (1), (3-7) showed the incorrect power flow but the objective function value is determined correctly and is the absolute minimum. For example, instead of power transmission by the only tie line in one direction (Fig. 2) represented by variable z_{13} from surplus node 1 to deficient node 3, the additional node 2 and tie lines z_{12} and z_{23} are used for power transmission, which is not necessary at all. Such a flow "through" additional node 2 increases power transmission losses.

We applied TS1 as a tested example, optimized model (1-5), (7) using PFGD, and in addition, we arranged testing with the aid of the commercial solver of linear programming problems LP Solve. The results obtained are presented in (Table 2).

Table 2. Test results, model (1) – (5), (7).

			PFGD	LP Solve
$\grave{x}_1$	158	x_1	103,94	101
$\grave{x}_2$	109	x_2	105,21	108
$\grave{x}_3$	83	x_3	83	83
$\grave{y}_1$	91	y_1	91	91
$\grave{y}_2$	98	y_2	98	98
$\grave{y}_3$	201	y_3	102	102
$\grave{z}_{12}$	10	z_{12}	2,94	0
$\grave{z}_{21}$	10	z_{21}	0	0
$\grave{z}_{13}$	10	z_{13}	10	10
$\grave{z}_{31}$	10	z_{31}	0	0
$\grave{z}_{23}$	10	z_{23}	10	10
$\grave{z}_{32}$	10	z_{32}	0	0
		a	0,05	0,05

The study presented in [12] suggested a transformation of the objective function (1) into the form

$$\sum_{i=0}^{n} (\grave{y}_i - y_i)^2/\grave{y}_i \to \min_{y}, i \neq j. \tag{8}$$

After replacement of objective function (1) by objective function (8) in model (1-5), (7), the obtained model (1-5), (7), (8) was tested on TS1. The test resulted in the values identical to those in Table 2. The obtained solution satisfies balance constraints (2) with an error of 0.003, where ***i***=2 (which can be referred to an error of the computer calculation because of representation of numbers in the PC memory). Hence, the emerge excess flow is expressed by the variable Z_{12}, which indicates an incorrect power flow Fig. 2. The obtained values of x_1, x_2, Z_{12} do not correspond to the reference solution. The analysis of the considered example on TS1 with the constraints presented in (Table 2) shows that the additional generating capacity in an amount of 2.79 MW from node 1 is used instead of the generating capacity in an amount of 108 MW of node 2 to transmit the power in an amount of 10 MW to node 3. This additional power was transmitted to node 3 through node 2. However, the value of Z_{12} equals 2.94 MW because of the inclusion of additional power transmission losses.

Thus, a set of the obtained parameters (Table 1) satisfies the stated conditions and constraints, in particular, the determined value of the objective function minimum, but is not an optimal solution in terms of power flow. Hence, the model aimed at the correct power flow cannot eliminate the cases of incorrect power flow.

Model (3-8) with nonlinear balance constraints was tested as an experiment, and the obtained results (Table 3) were close to the previous ones (Table 2). The results of additional testing via the commercial solver GAMS (the CONOPT module for solving the nonlinear programming problems) are also presented in Table 3.

Table 3. Test results, model (3-8).

			PFGD	GAMS
$\dot{x}_1$	158	x_1	103,27	101
$\dot{x}_2$	109	x_2	105,98	108
$\dot{x}_3$	83	x_3	83	83
$\dot{y}_1$	91	y_1	91	91
$\dot{y}_2$	98	y_2	98	98
$\dot{y}_3$	201	y_3	93	93
$\dot{z}_{12}$	10	z_{12}	2,27	0
$\dot{z}_{21}$	10	z_{21}	0	0
$\dot{z}_{13}$	10	z_{13}	10	10
$\dot{z}_{31}$	10	z_{31}	0	0
$\dot{z}_{23}$	10	z_{23}	10	10
$\dot{z}_{32}$	10	z_{32}	0	0
		a	0,05	0,05

As is seen from Table 3, the results satisfy the balance constraints with an error of -0.007645 when solving (6), where i=2 (which can be referred to the error of the computer calculation because of representation of numbers in the PC memory), and the excess flow expressed by the variable Z_{12} is available (Fig. 2).

In [14] there is a statement that the quadratic component in the balance equality constraints (6) stipulates the nonconvexity of a set of feasible solutions. However, based on the data obtained in two experiments we can suppose that on the whole, the model with quadratic losses has a set of optimal solutions. This fact, in turn, influences the power flow, thereby the objective function minimum is determined correctly. In order to confirm the availability of a set of feasible solutions, we made additional calculations on TS1 with different starting points specified for the gradient descent method. The results are presented below in Table 4, where the number in the heading is the serial number of the experiment, the first column of each experiment describes the values of the starting point parameter, the second column presents the obtained solutions.

Table 4. Test results of the multi-start PFGD use.

a = 0.00009				1		2		3	
$\dot{x}_1$	158	x_1		50	103,3	100	102,9	101	104,1
$\dot{x}_2$	109	x_2		50	105,7	100	106,1	108	104,9
$\dot{x}_3$	83	x_3		50	83	100	83	83	83
$\dot{y}_1$	91	y_1		50	91	100	91	91	91
$\dot{y}_2$	98	y_2		50	98	100	98	98	98
$\dot{y}_3$	201	y_3		50	103	100	103	102,9	103
$\dot{z}_{12}$	10	z_{12}		50	2,3	100	1,8	10	3,1
$\dot{z}_{21}$	10	z_{21}		50	0	100	0	0	0
$\dot{z}_{13}$	10	z_{13}		50	10	100	10	10	10
$\dot{z}_{31}$	10	z_{31}		50	0	100	0	0	0
$\dot{z}_{23}$	10	z_{23}		50	10	100	10	0	10
$\dot{z}_{32}$	10	z_{32}		50	0	100	0	0	0

Table 4 illustrates significant variations in the generating capacity values x_1 and x_2, and also a changing resultant value of the flow z_{12}. Therewith, the values of the supplied load y_1, y_2, y_3 do not vary, which indicates that the function minimum was determined correctly. Thus, the results show the existence of a set of feasible solutions. The authors of [14] proposed some modifications to solve this problem, in particular, with the quadratic constraints. The modifications concerned both the model and the calculation scheme. To start with, the authors made an attempt to eliminate a nonconvex set of feasible solutions by transforming balance constraints (2), (6) from the equality constraints to the inequality constraints. These constraints specified fully supplied load at the node and also assumed the maximum possible power transmission, which had to resolve the problem of incorrect power flow.

$$x_i - y_i + \sum_{j=1}^{n}(1 - a_{ji}z_{ji})z_{ji} - \sum_{j=1}^{n} z_{ij} \geq 0, \quad i = 1, \dots, n, i \neq j. \tag{9}$$

The application of the considered constraints on TS1 showed that the incorrect power flow remained, but the flow value z_{12} decreased, at the same time the generating capacity values x_1, x_2, x_3 changed and became equal to $\dot{x}_1, \dot{x}_2, \dot{x}_3$ respectively. However, the availability of generating

Table 5. Test results, model (1), (3-5), (7), (9).

			PFGD	GAMS
$\dot{x}_1$	158	x_1	158	101
$\dot{x}_2$	109	x_2	109	108
$\dot{x}_3$	83	x_3	83	83
$\dot{y}_1$	91	y_1	91	91
$\dot{y}_2$	98	y_2	98	98
$\dot{y}_3$	201	y_3	93	93
$\dot{z}_{12}$	10	z_{12}	0,22	0
$\dot{z}_{21}$	10	z_{21}	0	0
$\dot{z}_{13}$	10	z_{13}	10	10
$\dot{z}_{31}$	10	z_{31}	0	0
$\dot{z}_{23}$	10	z_{23}	10	10
$\dot{z}_{32}$	10	z_{32}	0	0
		a	0.05	0.05

capacity in the volume exceeding the volume needed to serve the load is physically unnatural, because this surplus capacity is blocked. For example, Table 5 displays the results obtained on TS1 using PFGD for model (1), (3-5), (9).

The authors of [14] proposed a theoretical approach to obtaining the optimal values of a solved problem with the correct power flow. The idea of the approach was to solve the problem by a two-stage optimization. The first stage suggests applying model (1), (3-5), (7), (8), obtaining an intermediate solution, and then introducing a new variable

$\grave{\Delta}_i, i = 1, \dots, n$

$$\tilde{\Delta}_i = \tilde{x}_i - \tilde{y}_i + \sum_{j=1}^{n}\left(1 - a_{ji}\tilde{z}_{ji}\right)\tilde{z}_{ji} - \sum_{j=1}^{n}\tilde{z}_{ij}, \quad i = 1, \dots, n, i \neq j, \tag{10}$$

$$\sum_{i=1}^{n}\Delta_i \to \min_{\Delta}, \tag{11}$$

$$x_i + \sum_{j=1}^{n}\left(1 - a_{ji}z_{ji}\right)z_{ji} - \sum_{j=1}^{n}z_{ij} - \Delta_i = \tilde{y}_i, \quad i = 1, \dots, n, i \neq j, \tag{12}$$

where $\tilde{\Delta}_i, \tilde{x}_i, \tilde{y}_i, \tilde{z}_{ji}$ is the optimal solution obtained in the first stage (10). In the second stage, the values of $\tilde{y}_i$ were fixed and a new objective function of form (11) and balance constraints of type (12) were introduced, subsequently the problem was solved for the variables Δ_i, x_i, z_{ji}, and the model took form (3-5), (7), (9), (11), (12), $j \neq i$, $i=1,\dots,n$, $j=1,\dots,n$.

The proposed modifications were validated on TS1 using PFGD. The values of the variables obtained in the first stage of the problem-solving process are presented in (Table 5). However, in the second optimization stage, the results did not change, which indicated that the results of this model were incorrect.

We propose the following algorithms to deal with incorrect power flow. The two-stage optimization must be applied in a different way: the power shortage minimization problem for model (1), (3-5), (7), (9) must be solved in the first stage. Such an approach will provide a convex set of feasible solutions. Then, the obtained optimal solutions for the variable y_i must be fixed and a new variable must be denoted as $\grave{y}_i$. Subsequently, in the second stage, it is necessary to generate a new objective function, which is the minimization of the second Euclidean norm for all the flows:

$$\sum_{i=1}^{n}{z_{ji}}^2 \to \min_{z}, i \neq j, \tag{13}$$

and also to transform the current balance constraints (10) into the balance constraints presented below:

$$x_i - \tilde{y}_i + \sum_{j=1}^{n}\left(1 - a_{ji}z_{ji}\right)z_{ji} - \sum_{j=1}^{n}z_{ij} = 0, \quad i = 1, \dots, n. \tag{14}$$

The performance of the approach of the sequential two-stage optimization and the interaction of models (1), (3-5), (7), (9) and (4-5), (7), (13), (14) was validated on TS1 using PFGD. The results of the first stage are presented in Table 5, the parameters obtained in the test of the second stage are indicated in Table 6.

Table 6. Test results, model (4-5), (7), (13), (14).

			PFGD	GAMS				PFGD	GAMS
$\grave{x}_1$	158	x_1	99,5	101	$\grave{x}_1$	158	x_1	100,98	101
$\grave{x}_2$	109	x_2	106,5	108	$\grave{x}_2$	109	x_2	107,98	108
$\grave{x}_3$	83	x_3	83,11	83	$\grave{x}_3$	83	x_3	83	83
$\grave{y}_1$	91	y_1	91	91	$\grave{y}_1$	91	y_1	91	91
$\grave{y}_2$	98	y_2	98	98	$\grave{y}_2$	98	y_2	98	98
$\grave{y}_3$	93	y_3	93	93	$\grave{y}_3$	103	y_3	102,98	103
$\grave{z}_{12}$	10	z_{12}	0	0	$\grave{z}_{12}$	10	z_{12}	0	0
$\grave{z}_{21}$	10	z_{21}	0	0	$\grave{z}_{21}$	10	z_{21}	0	0
$\grave{z}_{13}$	10	z_{13}	8,49	10	$\grave{z}_{13}$	10	z_{13}	9,98	10
$\grave{z}_{31}$	10	z_{31}	0	0	$\grave{z}_{31}$	10	z_{31}	0	0
$\grave{z}_{23}$	10	z_{23}	8,49	10	$\grave{z}_{23}$	10	z_{23}	9,98	10
$\grave{z}_{32}$	10	z_{32}	0	0	$\grave{z}_{32}$	10	z_{32}	0	0
		a	0,05	0,05			a	0,00009	0,00009

Table 7. Test results, model (4-5), (7), (14), (15), PFGD.

	Experiments				
	1	2	3	4	5
$\grave{x}_1$	158	150	100	250	158
$\grave{x}_2$	109	150	150	140	109
$\grave{x}_3$	83	100	200	100	83
$\grave{y}_1$	91	150	100	150	91
$\grave{y}_2$	98	250	150	150	98
$\grave{y}_3$	201	150	100	200	201
$\grave{z}_{12}$	10	50	50	50	10
$\grave{z}_{21}$	10	50	50	50	11
$\grave{z}_{13}$	10	50	50	50	12
$\grave{z}_{31}$	10	50	50	50	13
$\grave{z}_{23}$	10	50	50	50	14
$\grave{z}_{32}$	10	50	50	50	15
a	0,05	0,05	0,05	0,05	0,05
	1	2	3	4	5
x_1	100,43	150	100	168,58	100,43
x_2	107,43	150	150	140,01	107,43
x_3	83,02	100	100	100,01	83,02
y_1	91	150	100	150	91
y_2	98	150	150	145	98
y_3	93	100	100,01	105	93
z_{12}	0	0	0	9,29	0
z_{21}	0	0	0	0	0
z_{13}	9,43	0	0	9,29	9,43
z_{31}	0	0	0	0	0
z_{23}	9,43	0	0	0	9,43
z_{32}	0	0	0	0	0

The results in Table 6 show that the parameters obtained with this combination of models are adequate and close to the target values of the commercial solver GAMS. The more exact and closer results were obtained by modification of the objective function of model (13) of the second stage that is given below:

$$\sum_{i=1}^{n} x_i \to \min_{x}. \qquad (15)$$

The objective function (16) is intended for minimization of generating capacity, which can yield a positive economic effect in power generation and distribution. Model (4-5), (7), (14), (15) with this objective function for the second optimization stage was validated on TS1 and showed closer and more valid results than model (4-5), (7), (13), (14). The calculation results are illustrated in Table 6, the values of the constraints are presented in the upper part and the results are given in the lower part.

IV. Methods for power shortage minimization in power systems

The penalty function method [15] can be applied to optimization problems with different types of constraints. This method makes it possible to transform the initial problem with constraints into the problem that can be solved by the unconstrained optimization methods. Such a transformation allows the use of simpler methods for solving the linear and nonlinear programming problems and the increase in calculation accuracy with the correct selection of parameters. The main changes occur in the objective function, to which the constraints in the form of penalty functions are added. Thus, changes in the system can lead to automatic involvement of the penalty function, whose value will sharply rise. In this case, the response to the penalty will be controlled by the optimization method, and finally, the function will be directed to a sought solution. There are two subtypes of the penalty function method – internal and external penalty functions.

Further, we will consider the external penalty function method, since this method allows solving the constrained optimization problems with both equality and inequality constraints. In the general form, the function and constraints look as follows:

$$f(x) \to min, \qquad (16)$$

subject to equality and inequality constraints:

$$\varphi_i(x) = 0, i = 1, \ldots, I, \qquad (17)$$

$$g_j(x) \le 0, j = 1, \ldots, J, \qquad (18)$$

The strategy of a search for the optimal solutions suggests that in this method the penalty functions *Φ(x,γ)* are chosen so that their values are equal to zero inside and on the boundary of the feasible region *G*, while beyond the region they are positive and increase the more, the higher the violations of the constraints. Thus, here the distance from the feasible region *G* is "penalized".

As a rule, the function:

$$\Phi(x, \gamma) = \frac{\gamma}{2} \qquad (19)$$

where:

$$max\left(0, g_j(x)\right) = \begin{cases} 0, g(x) \le 0 \\ g_j(x), g_j(x) > 0 \end{cases} \qquad (20)$$

is applied as an external penalty function.

The auxiliary function *F(x,γ)*, in this case, takes the form:

$$F(x, \gamma) = f(x) + \Phi(x, \gamma)\,. \qquad (21)$$

The starting point for search is usually specified beyond the feasible region *G*. The point x^* (γ^k) of the unconstrained minimum of the auxiliary function $F(x^*,\gamma^k)$ for x with the specified parameter γ^k is searched with the help of any method of constrained optimization (of the zero, first or second order) at each k-th iteration. The obtained point x^* (γ^k) is used as a starting one at the next iteration with the increasing value of the penalty parameter. With the unlimited growth of γ^k the sequence x^* (γ^k) converges to the constrained minimum point x^*.

V. Application of the penalty function method to power shortage minimization problem

We apply the described method to transform the stated constrained optimization problem with the balance constraints subject to the quadratic losses. Then, we generate an auxiliary function by integrating the constraints in a required format into the external penalty function for model (1), (3-6), (8), (10), which will look as follows:

$$\Phi(x, y, z, a, \dot{x}, \dot{y}, \dot{z}, \gamma) = \frac{\gamma}{2} \qquad (22)$$

The value of the penalty multiplier is controlled by the parameter γ. In this problem, the penalty is gradually increased by an order of magnitude per iteration, the initial value of this parameter is equal to 10. The remaining penalty function parameters are correlated in accordance with the

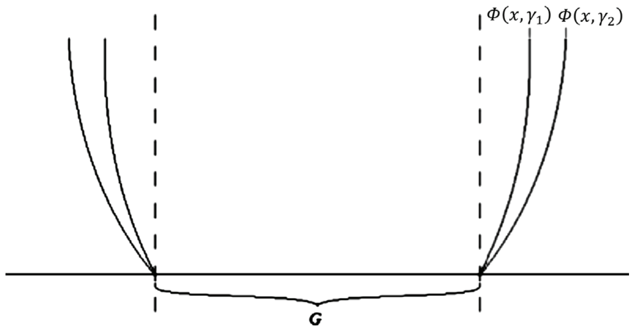

Fig. 3. Graph of the strategy of search (with $\gamma_2 > \gamma_1$).

available constraints, where the equality constraints are the penalty function parameters:

$$\varphi_i(z) = z_{jk} * z_{kj}, \quad i = 1, \dots, I, j = 1, \dots, n, k \neq j \tag{23}$$

The inequality constraints are:

$$max\left(0, t_j(x, y, z, a)\right) = \begin{cases} 0, t_j(x, y, z, a) \leq 0 \\ t_j(x, y, z, a), t_j(x, y, z, a) > 0 \end{cases}, \quad j = 1, \dots, n, \tag{24}$$

$$t_j(x, y, z, a) = x_i - y_i + \sum_{k=1}^{n}(1 - a_{ki}z_{ki})z_{ki} - \sum_{k=1}^{n} z_{ik} \tag{25}$$

$$j = 1, \dots, n, k = 1, \dots, n, i = 1, \dots, n, k \neq i,$$

$$max\left(0, g_j(x)\right) = \begin{cases} 0, g(x) \leq 0 \\ g_j(x), g_j(x) > 0 \end{cases}, \quad j = 1, \dots, n, \tag{26}$$

$$max\left(\dot{x}, g_j(x)\right) = \begin{cases} \dot{x}, g(x) \geq \dot{x} \\ g_j(x), g_j(x) < \dot{x} \end{cases}, \quad j = 1, \dots, n, \tag{27}$$

$$max\left(0, g_j(y)\right) = \begin{cases} 0, g(y) \leq 0 \\ g_j(y), g_j(y) > 0 \end{cases}, \quad j = 1, \dots, n, \tag{28}$$

$$max\left(\dot{y}, g_j(y)\right) = \begin{cases} \dot{y}, g(y) \geq \dot{y} \\ g_j(y), g_j(y) < \dot{y} \end{cases}, \quad j = 1, \dots, n, \tag{29}$$

$$max\left(0, g_j(z_{ki})\right) = \begin{cases} 0, g(z_{ki}) \leq 0 \\ g_j(z_{ki}), g_j(z_{ki}) > 0 \end{cases}, \quad j = 1, \dots, n, k = 1, \dots, n, i = 1, \dots, n, k \neq i \tag{30}$$

$$max\left(\dot{z}_{ik}, g_j(z_{ik})\right) = \begin{cases} \dot{z}_{ik}, g(z_{ik}) \geq \dot{z}_{ik} \\ g_j(z_{ik}), g_j(z_{ik}) < \dot{z}_{ik} \end{cases}, \quad j = 1, \dots, n, k = 1, \dots, n, i = 1, \dots, n, k \neq i. \tag{31}$$

Further, we replace the objective function f(x), and also penalty functions (23) and (26) in accordance with the replaced balance constraints by (15), however, (24), (27) – (32) are not subject to changes. In the end, the penalty functions must be of the following form:

$$\Phi(x, \tilde{y}, z, \dot{x}, \dot{y}, \dot{z}, \gamma) = \frac{\gamma}{2} \tag{32}$$

where:

$$\varphi_i\left(x, \tilde{y}, z_{ji}, a_{ji}\right) = x_i - \tilde{y}_i + \sum_{j=1}^{n}\left(1 - a_{ji}\right)z_{ji} - \sum_{j=1}^{n} z_{ij}, i = 1, \dots, n. \tag{33}$$

VI. Conclusion

The assessment of power system adequacy is topical and necessary for power system expansion planning. The power shortage minimization problem is solved within the system adequacy assessment by the Monte Carlo method. The paper presents an analysis of the existing power shortage minimization models. The study revealed some downsides of the models. A case study demonstrates that the models have a nonconvex set of feasible solutions. The paper describes a technique for transformation of balance constraints for modeling of the problem with a set of feasible solutions. Consideration is also given to different modifications of the power shortage minimization models. Based on the studies performed we propose two modifications of the models.

The stated problems were solved by the gradient descent method. The commercial solvers GAMS (CONOPT) and LP Solve were applied to obtain reference solutions.

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Implementation Of International Corporate Governance Standards In Russian Electric Power Industry

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Abstract — **The paper considers the implementation of international corporate governance standards in Russian power generation companies. The implementation is mainly determined by analyzing whether or not Russian companies comply with Russia's Corporate Governance Code criteria that are based on these standards. An in-depth analysis involves additional assessments. These are the assessment of Russian boards of directors by Spencer Stuart; the Transparency International assessment of corporate reporting transparency in the largest Russian companies; the assessment of the Corporate Governance Index of Russia based on the Good Governance Index and an international methodology adapted to Russian contexts; and the assessment of how the elements of the international "soft law" are introduced. These additional assessments made it possible to consider the criteria that are not included in the Code; to compare corporate practice in the Russian power generation companies with other Russian companies and the largest companies in Europe, the United Kingdom and the United States; and to study independent opinions of professional and expert communities about the quality of corporate governance. The findings revealed that the overwhelming majority of Russian power generation companies do not meet the analyzed criteria that are significant for investors. This situation is indicative of weak implementation of international corporate governance standards in these companies and their low investment attractiveness.**

Index Terms — **Corporate governance, international standards, implementation, Russian power generation companies.**

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I. Introduction

The world experience of corporate governance shows that it is impossible to ensure the inflow of foreign investment and the successful development of companies without an effective management system. Such a system helps determine the goals of a company and the methods of their achievement, and constantly monitor the activity of the company. High quality corporate governance provides access to capital markets and reduces its cost, gives investors confidence that the capital they provide will increase the company's capitalization, and will not be appropriated by corporate executives, the board of directors or controlling shareholders; that investors will participate in company's profit on fair and equal terms. Good corporate governance, coupled with effective control and enforcement mechanisms, can increase the level of confidence not only of external, but also of Russian investors, strengthen the proper operation of financial markets and, ultimately, stimulate more stable sources of funding [1]. Such management makes it possible to strengthen the position of any country in the World Bank Doing Business rating, in particular, due to the high "index of protection of the rights of minority investors", especially noted by the Government of Russia in the "Improving corporate governance" roadmap [2]. The implementation of international corporate governance standards that are trustworthy and understandable for any investors, contributes to its quality in Russian companies.

Russian experience of corporate governance based on the international standards is relatively small. The basic milestone of their introduction into the Russian corporate practice was the Code of Corporate Conduct (2002). In the Russian electric power industry, the experience of corporate governance is even smaller. Partly, the low investment attractiveness of Russian power generation companies is caused by the problems associated with the establishment of new corporate relations that are adequate to the altered realities. After restructuring and privatization (2008), in most of them the effective owners did not appear. The formation of new corporate relations was exacerbated by other external conditions in comparison with the creation of "typical" world models of corporate governance - "Anglo-American" and "German". Such specificity, in particular, was due to the relative weakness of the Russian securities market and the banking system, legal institutions, law enforcement practices, the lack of competitiveness of the commodity, capital and labor markets.

The Code of Corporate Governance of Russia (Code) (2014) was another milestone in the improvement of Russian corporate practice. This Code clarifies the best standards of corporate governance practice for observing the rights of shareholders that meet new needs, contributes to their practical implementation, and acts as an effective tool to improve the efficiency of company management and ensure its long-term and sustainable development. This document considers the improvement of corporate governance «... as the most important measure to increase investment flows to all sectors of the Russian economy, both from sources within the country and from foreign investors» [3]. The main purpose of applying the international standards in the Russian practice of corporate governance is to protect the interests of all shareholders, regardless of the size of their block of shares. The higher the level of protection of shareholders' interests, the greater number of Russian companies will be able to count on large investments.

The ultimate goal of this study was to determine the current implementation of international corporate governance standards in the Russian electric power industry, given the nation-specific contexts. Modern international standards of corporate governance G20/ OECD are shown. The implementation of international standards in the practice of corporate governance of 13 Russian power generation companies from the RBC-500 list was comprehensively analyzed [4]. The analysis was mainly based on the criteria for compliance of corporate governance in these companies with the principles of the Code [5-17]. For a more in-depth analysis, additional assessments have been studied. These are the assessment of Russian boards of directors by the company Spencer Stuart [18–21]; the assessment of the transparency of corporate reporting of the largest Russian companies by the organization Transparency International [22]; the assessment of objective signs and opinions of the respondents of the Corporate Governance Index of Russia regarding good corporate practices [23–25]. The additional assessments were necessary to study the implementation of the international standards according to the criteria that are not included in the Code. It was also necessary to analyze the implementation according to the views of the professional community and in comparison with other Russian companies, the largest companies in Europe, the United Kingdom and the United States. The introduction of the international "soft law" elements into the practice of corporate governance of Russian power generation companies, which are used in the countries with relatively weak legal and regulatory frameworks was analyzed [27, 28].

II. International corporate governance standards

International standards (principles) of corporate governance determine the global policy and practice of corporate governance. They first appeared in 1999 as a result of the compilation of data on corporate governance in the member-countries of the Organization for Economic Cooperation and Development (OECD). In 2014-2015, these standards were revised and approved as the G20 / OECD Corporate Governance Principles (G20 / OECD Principles). Below they are listed in an updated form [1].

1. The corporate governance should stimulate transparent and fair markets and efficient allocation of resources. It must comply with the requirements of the rule of law and support effective oversight and enforcement.
2. The corporate governance should protect the rights of shareholders and ensure fair and equal treatment of all shareholders, including minority and foreign shareholders. All shareholders should be able to receive effective compensation for violation of their rights.
3. The corporate governance must provide strong incentives throughout the entire investment chain and require securities markets to operate so as to promote good corporate governance.
4. The corporate governance should recognize the rights of stakeholders as provided by law or by multilateral agreements, and stimulate active cooperation between corporations and stakeholders in the light of creation of wealth, jobs, and financially sustainable enterprises.
5. The corporate governance should ensure timely and accurate disclosure of information on all essential company–related matters, including financial position, results of operations, ownership and management.
6. The corporate governance should provide strategic management of the company, effective control over management by the board of directors, and the accountability of the board of directors to the company and shareholders.

The G20 / OECD principles reflect global corporate governance experience since 1999, including changes in the corporate and financial sectors. They retain the same key elements of creating an effective corporate governance system: high transparency; accountability; supervision by the board of directors; respect for shareholder rights; the importance of the role of key stakeholders.

These principles are generally recognized in the world, including the developing and emerging economies that are interested in attracting investment. They are considered to be guidelines for policy makers, investors, companies and other stakeholders and a key standard of sustainable financial systems, the basis for the World Bank reports on compliance with corporate governance standards and codes. The G20 / OECD principles can be used to improve corporate practice not only by companies whose shares are traded at the open securities market, but also by those whose shares are not listed on the stock exchange.

The key elements of an effective corporate governance system, clearly defined in the G20 / OECD Principles, are applied in global corporate practice in accordance with the economic, legislative, social and regulatory features of each country. In Russia, they were used as basic principles for the development of the Russian Code. The development of the Code allowed for the national contexts and involved the European Bank for Reconstruction and Development, the OECD, the Moscow Exchange, the Federal Property Management Agency and the Ministry of Economic Development of Russia, Russian and international companies providing services in the field of corporate management.

III. Implementation of international standards according to the compilance criteria

The current implementation of international standards in the corporate practice of Russian power generation companies has been studied on the example of 13 companies from the RBC-500 list. These are PJSC "Inter RAO UES", PJSC "OGK-2", PJSC "Unipro", PJSC "Enel Russia", PJSC "RusHydro", PJSC "TGC-1", OJSC "TGC-2», PJSC «Mosenergo», PJSC «Quadra», PJSC «Irkutskenergo», PJSC "T Plus", OJSC «Fortum», PJSC «TGC-14»[4]. Implementation was determined mainly by analyzing:

A. The compliance with the principles of the Code.
B. The assessment by Spencer Stuart.
C. The assessment by Transparency International.
D. The Russian Corporate Governance Index.
E. The introduction of the international "soft law" elements.

A. Compliance with the principles of the Code

The principles of the Code are generalized below [3]. The generalization meets the recommendations of the Bank of Russia that are intended for Russian companies to make the "Reports on Compliance with the Principles and Recommendations of the Corporate Governance Code" in the framework of their Annual Reports (Bank of Russia Letter dated February 17, 3016 No. IN - 06 - 5218).

1. The system and practice of corporate governance should ensure equality of conditions for all shareholders owning shares of the same category, including minority (small) shareholders and foreign shareholders, an equal and fair attitude towards them when exercising the right to participate in the management of the company and profits through dividends.
2. The company board of directors should be an effective and professional governing body in the interests of the company and its shareholders, exercise strategic management, control the activities of the executive bodies, and be accountable to the shareholders.
3. The corporate secretary should ensure effective ongoing interaction with shareholders, coordination of actions to protect their rights and interests, effective work of the board of directors.
4. The system of remuneration of board of directors, executive bodies and other key managers should ensure the remuneration dependence on the result of the company's work and their personal contribution to the achievement of this result. Remuneration must be paid in accordance with the accepted remuneration policy. The remuneration system for members of the board of directors should bring closer the financial interests of directors to the long-term financial interests of shareholders.
5. A system of risk management and internal control should be established in the company to achieve its goals. It is necessary to make a systematic and independent assessment of its reliability and efficiency.
6. Timely disclosure of complete, current, reliable and additional material information about the company and its subsidiaries should be carried out to enable the shareholders and investors to make informed decisions. The provision of information must comply with the principles of fairness and ease.
7. The procedure for conducting material corporate actions should be developed in the company (increase in share capital, takeover, listing and delisting of securities, reorganization, material deals). These actions can significantly affect the structure of share capital and the financial standing of the company, and, as a result, the position of shareholders. This procedure should allow shareholders to timely receive full information on material actions, to influence their performance and guarantee respect for their rights and adequate level of their protection.

In order to analyze the compliance of the Russian power generation companies with the principles of the Code, a total of 128 criteria were used to assess the compliance with these principles. These criteria are contained in the recommendations of the Bank of Russia, which, unlike the previous recommendations of the Moscow Exchange, present the corporate governance principles in a clearer structure, highlight the criteria for the assessment of their compliance, expand the status of compliance with each of the principles, and specify the form of explanations why the criteria are not met.

The analysis revealed numerous violations of the criteria for assessing the compliance of the companies with the principles of the Code. The principles that are not respected by the overwhelming majority of companies (in brackets - the proportion of companies that meet these criteria, in percentage of the total number of companies) are given below.

- Shareholders are provided with information on who nominated candidates to the board of directors (33).
- The board of directors includes at least 1/3 of independent directors (33).
- Information on attendance of meetings of the board of directors and its committees by individual directors is disclosed (33).
- The data on beneficiaries and other shareholders are disclosed (32).
- Principles and approaches to the organization of a risk management and internal control system are defined (25).
- The board of directors is notified of the intentions or appointments of its members in the governing bodies of other organizations (25).
- A policy is developed and implemented to remunerate members of the board of directors, executive bodies and other executives, including transparent mechanisms for determining the remuneration (25).
- The list of transactions and other material corporate actions, the criteria for determining them are defined (25).
- The content of the Code of Ethics is disclosed (23).
- The effectiveness of the risk management and internal control system is assessed (20).
- The most important issues are considered at in-person board meetings (17).
- The committees of the board of directors for audit, and remuneration consist only of independent directors. At least one member of the audit committee has experience and knowledge in the preparation, analysis and audit of financial statements (17).
- All committees of the board of directors are headed by an independent director (17).
- Board of directors considers the issues of corporate governance practices (16).
- The content of the Corporate Governance Code is disclosed (15).
- Board of directors considers the information policy compliance issues (15).
- Procedures are adopted to assess the compliance of the quantitative composition of board of directors with the needs of the company, the effectiveness of its individual members, committees and the board of directors as a whole; and analyze the professional qualifications of the board members, their experience, knowledge and business skills, absence of conflict of interests, etc. (8).
- Shareholders are provided with the biographical data of all candidates for the members of board of directors, results of evaluation of such candidates, information on compliance with the independence criteria when electing the board of directors (8).
- There is a procedure for independent directors to evaluate and approve the material corporate actions prior to their implementation (8).
- There is an expanded list of grounds on which members of the board of directors are recognized as interested in the transactions of companies (8).
- Information on the relationship between remuneration of the board members and performance of the company is disclosed (7).
- Detailed information on the remuneration of members of the board of directors is disclosed (0).
- Detailed information on remuneration of management bodies is disclosed (0).

The criteria listed above are of particular importance to investors. This is confirmed by their high correlation with the indicators of good corporate governance of the Corporate Governance Index of Russia (Index 2017), which is based on the international Good Governance Index methodology adapted to Russian conditions [24,25]. It is worth noting that more than 70% of the unobserved criteria of the Code are directly related to the boards of directors of companies. For this reason, in particular, in order to better understand the implementation of international standards in the corporate practice of the Russian power generation companies, the assessment of the Russian boards of directors by Spencer Stuart was analyzed.

B. Assessment by Spencer Stuart

The Spencer Stuart "Board Index" is an annual survey for various countries that analyzes various aspects of board performance. The analysis covers the boards of directors of large public companies. It was first published over 30 years ago in the United States. Today it is produced in 22 countries, including 11 European countries. The first edition of the Russian board of directors Index was published by Spencer Stuart in 2014. The main objective of this Index is to provide business leaders with current information on current practices in Russian boards of directors. In addition to these data, Spencer Stuart publishes detailed information on a number of key management indicators of Russian boards of directors compared with the boards of the largest companies in Europe, the United Kingdom and the United States. The Russian companies included in the Russian board of directors Index have large market capitalization in terms of the RTS index in each year of the study. The Russian power generation companies included in the Spencer Stuart Russian Index of the board of directors (2014–2017) are represented only by PJSC "Inter RAO UES" and PJSC "RusHydro", PJSC "Mosenergo" was added to this list in 2015 and 2017.

Generalized indicators of the corporate governance quality that are assessed by Spencer Stuart, are given below (in brackets - the number of criteria for each of them) [18–21]:

1) The size and composition of the board of directors

a) executive and non-executive directors (3);
b) independent directors (2);
c) female representation on board of directors (6);
d) directors from outside Russia (5);
e) new directors (3);
e) average age of directors (6);
g) tenure (3);
h) number of directors serving on an outside company board (4);
i) the number and type of committees on board (4).

2) Meetings and performance evaluation of board

a) meetings of board of directors (2);
b) performance evaluation of board (2).
3) remuneration of directors
a) chairman of board (2);
b) non-executive directors (2);
c) remuneration for participation in committees (3)

Among the listed indicators, particular attention was paid to those non-observed by the overwhelming majority of Russian power generation companies, which were revealed during the study of the Code. These are independent directors, performance evaluation of board of directors, and their remuneration. Assessment of these Spencer Stuart indicators provided additional information on the implementation of the international standards in comparison with other Russian companies and the largest companies in Europe, the United Kingdom and the United States. Indicators concerning independent directors are particularly significant. This importance is explained by high concentration of ownership in the Russian power generation companies, the lack of effective external corporate control by banks and the stock market. The studies indicate that the average index of independent directors on boards in these companies is relatively low and in 2016 was less than 27%. This value is lower than similar indicator in Russian companies - 36.7% and the lowest among those in Europe and the USA. The highest proportions of independent directors according to Spencer Stuart are noted on boards of directors in companies in the Netherlands, Finland and Switzerland — 84%, and the United States - 85% [21].

The study noted almost absent internal and external evaluation of the performance of boards of directors. The Code recommends that companies conduct an annual self-assessment, and the assessment involving an external organization, at least once every three years. However, there is no uniform methodology for internal performance evaluation of boards of directors. The Code does not provide it either but puts forward recommendations that are limited only to a simple listing of individual criteria - "... professional and personal qualities of board members, their independence, coherence and degree of participation in the work" [3]. Often, an internal assessment is reduced to a simple questioning of board members on various organizational issues. As a result, neither the shareholders nor the boards of directors themselves know what to do with its results and refuse it. According to Spencer Stuart, PJSC "Inter RAO UES" conducted internal performance evaluation of boards of directors in 2014–2015, and in 2016 - with the help of third-party organizations. The PJSC «RusHydro» conducted only self-assessment in 2014, 2015. The PJSC "Mosenergo" had neither self-assessment nor the assessment involving external organizations. Of all Russian companies surveyed by Spencer Stuart, only 19% evaluated the performance of boards of directors in 2016. For these companies, this is an obvious increase compared to 11% in 2015 and 6% in 2014 [19–21]. However, the achieved values are still far from those of the largest public foreign companies. In particular, in 2016 they accounted for 43.3% in the UK, 29% in Italy, and 28% in the Netherlands [21].

The study indicated low disclosure of information on remuneration of board of directors. According to Spencer Stuart, the confidentiality of such information, along with the heterogeneity of reporting standards makes it difficult to obtain this information. The overwhelming majority of Russian companies only disclose data on total remuneration for all members of the board of directors. In 2016, the average base remuneration of non-executive directors (excluding the chairman) in Russian companies was 105.934 Euro, in the US companies – 108.771 Euro. The amount of remuneration appeared to be comparable with virtually incomparable levels of corporate governance quality in these companies [21].

C. Assessment by Transparency International

In order to conduct an in-depth assessment of the implementation of international standards in Russian power generation companies, an additional analysis of the transparency of their corporate reporting was carried out according to the criteria of the organization Transparency International [22]. The study performed by the Transparency International on the "Transparency in corporate reporting: assessing Russia's largest companies" uses the same methodology as the study of "Transparency in corporate reporting: assessing the world's largest companies". Transparency International assesses the transparency of companies using three indicators underlying its index. These indicators are listed below. The number of criteria used by Transparency International for each studied indicator is shown in parentheses.

- Anti-corruption programs (13).
- Organizational transparency - disclosure of a full list of subsidiaries and associates, joint ventures and other controlled companies (8).
- Reporting by country of operation i.e. the countries where the company is present directly or indirectly through its subsidiaries and associates, joint ventures, branches and representative offices (5).

- The transparency of the corporate reporting of Russian power generation companies in 2016 was investigated according to the following key criteria of indicators of the Transparency International Index (in brackets - the share of companies that met these criteria, in percentage of the total number of companies)
- Company has a developed anti-corruption policy (30);
- A full list of subsidiaries and associates, joint ventures and other controlled entities is disclosed (0);
- Data on offshore zones of subsidiaries and associates, joint ventures and other controlled entities are provided, their financial data are disclosed (0).

The study revealed that the overwhelming majority of the Russian power generation companies had not developed an anti-corruption policy. The companies did not disclose: a full list of subsidiaries and associated companies, joint ventures and other controlled entities; data on offshore zones of their activities; financial data in these zones. It is worth noting that compliance with the above criteria for transparency of corporate reporting is of particular importance for investors of the companies, particularly those with high offshore ownership. Especially as the offshore ownership is characteristic of Russian power generation companies and has increased significantly in the post-restructuring years [26]. Two companies with high offshore ownership (PJSC "T Plus" and Siberian Generating Company LLC) were among the Russian companies investigated by Transparency International. They got a relatively low average corporate reporting transparency index for all of its three indicators. This index for PJSC "T Plus" was 4.4, and for Siberian Generating Company LLC - 0.9 (out of 10 points for the companies with the greatest transparency). The values of this index were slightly higher for the state-owned power generation companies - 5.2 – for PJSC "Inter RAO UES" , and 5.1 – for PJSC "RusHydro" [22].

D. The Russian Corporate Governance Index

The Russian Corporate Governance Index (hereinafter referred to as the Index) was developed by the Association of Independent Directors together with the National Research University "Higher School of Economics", the Bank of Russia, the Moscow Exchange and the Russian Union of Industrialists and Entrepreneurs twice (2016, 2017). The index is designed to understand what, in fact, is "good corporate governance" in Russian companies through the "eyes" of modern investors. The index was based on the Good Governance Index, an international methodology developed by the Institute of Directors of the United Kingdom and the Cass Business School (2015), and adapted to Russian conditions. In the Index, the basic principle of the international approach remains unchanged. According to this principle, corporate governance of each company is assessed based on two sources of information:

1. Results of electronic survey of representatives of the professional and expert communities (respondents) about the level of corporate governance in each company through the "eyes" of market participants, based on their subjective perception;
2. Reports and other publicly available sources about the company activities. These are used to evaluate individual indicators (objective signs of the corporate governance quality).

In the methodology of Index 2016, objective indications of the corporate governance quality were mainly associated with the Russian Code [23]. In Index 2017, the developers "... managed to move away from excessive attention to the Code and - following the recommendations of the British Institute of Directors - to make wider use of corporate behavior indicators promoted by well-known analytical and information agencies" [24]. This approach is fully correlated with the approach of the present study.

The international partners that developed the Good Governance Index determined which objective requirements for the quality of corporate governance affect its positive perception by investors. Given these requirements, a compact set of 34 indicators characterizing corporate governance in the areas recommended by the British Institute of Directors (board of directors, audit and risks, remunerations, relations with shareholders and relations with stakeholders) was investigated in the Index 2017. To reflect Russian specifics, they additionally took into account changes in the listing requirements of the Moscow Stock Exchange, the familiarization of large Russian companies with the standards of the Code, and the possibility of obtaining information from publicly available sources. "Relations with stakeholders" is a new direction in the study of Index 2017. It corresponds both to the prospects for the development of Russian corporate governance, and to the methodology of the British Institute of Directors [24]. In our opinion, it is almost impossible to use this indicator of the British Institute of Directors when assessing current Russian corporate practice. In contrast to the G20 / OECD Principles, "relations with stakeholders" are not considered in the Code as a separate principle, therefore, there are no recommendations (indicators) for its observance. The indicators proposed by some analytical agencies for Russian companies in this area were tested in the Index 2017.

The Index 2017 study involved 53 Russian companies whose shares were included at the end of the first quarter of this year in the first listing of Moscow Exchange. Consequently, the Russian power generation companies were represented by PJSC "Inter RAO UES", PJSC "Mosenergo", PJSC "TGC-1", PJSC "RusHydro", PJSC "Enel Russia" and PJSC "Unipro". According to a survey of respondents, the companies whose rating was higher than average (equal to 688 points) had good corporate governance. These companies are listed in Table 1.

The data in Table 1 show that, according to a survey of respondents, none of the Russian power generation companies were included in the list of companies with good corporate governance.

Among those assessed by objective grounds, only PJSC "Inter RAO UES" from the Russian power generation companies received a higher than average rating and was among the ten companies with good corporate governance in Index 2017.

E. Adoption of the international "soft law" elements

As noted above, "... the purpose of applying international standards in Russian corporate practice is to protect the interests of all shareholders, regardless of the size of the block of shares they possess. The higher the level of protection of shareholder interests, the larger the investment can be expected by Russian companies" [3]. In the international practice of corporate governance, «... when building protection for investors, a distinction must be made between the expected (ex ante) and actual (ex post) rights of shareholders. Expected rights, for example, include the preemptive right to purchase shares and make certain decisions by a qualified majority. Actual rights allow seeking compensation for damage in case of violation of rights. In the countries with insufficiently developed legal and regulatory frameworks, it is recommended to strengthen the expected rights of shareholders, for example, by setting a low threshold for the number of shares giving the right to put issues on the agenda of the general meeting of shareholders, or by providing an over-qualified majority of votes of shareholders to make important decisions» [1].

Table 1. Companies with good corporate governance according to respondents (2017).

Companies (PJSC)	Average assessment	Number of assessments
"Moscow exchange"	870	59
"Mts"	808	64
"Lukoil"	803	58
"Novatek"	792	26
"Sberbank"	772	122
"Transcontainer"	771	31
"Severstal"	765	23
"Aeroflot"	762	105
PJSC "NLMK"	752	21
"Mmc norilsk nickel"	744	46
"Alrosa"	739	46
"Afk sistema"	739	57
"Magnet"	737	49
"Megafon"	724	38
"Cherkizovo group"	721	14
"Pole"	721	14
"Phosagro"	711	9
"M-video"	710	29
"Mmk"	706	16
"Pik group of companies"	705	19
"Lsr group"	693	15

The implementation of international standards in Russian corporate practice requires strengthening the expected rights of shareholders in connection with noted violations of the use of capital provided by investors in companies and relatively weak legal and regulatory frameworks in the country. In part, such strengthening is incorporated in the fundamental principles of the Code, along with the key elements of international corporate governance practice - high transparency, accountability, oversight by the board of directors, and respect for the rights of shareholders. The expected rights of shareholders in the previously listed principles of the Code should be strengthened, in particular, to ensure effective interaction with shareholders and coordination of actions aimed at protecting their rights and interests; to improve the remuneration of company management; to create a risk management and internal control system; and to develop the procedures for conducting material corporate actions. These elements of corporate governance are formulated in the Code as independent principles.

International corporate governance standards for the countries with relatively weak legal and regulatory frameworks provide that "... legal and regulatory elements of a corporate governance structure can be practically supplemented with elements of "soft law" based on the "comply or explain" principle, for example, on the Corporate Governance Codes, providing flexibility and reflecting the specific features of individual companies" [1]. The formal attitude of the majority of Russian power generation companies to the introduction of elements of international "soft law" is noted. Own Corporate Governance Codes and Codes of Ethics in internal documents from the official websites of these companies are characterized by poor disclosure of their content. This is mainly explained by the fact that they are not updated. The content of the Corporate Governance Codes has not changed since 2006 in 85% of companies, Codes of Ethics - in 63% of companies, despite the updated principles of corporate governance and criteria for their observance in the Code (2014) that are approved and recommended by the Bank of Russia for the joint-stock companies, state corporations and companies.

The application of the "comply or explain" principle recommended by the Bank of Russia to Russian companies in evaluating their compliance with the principles of the Code is also very formal. This was confirmed by the monitoring of the quality of explanations by power generation companies of their non-compliance with the principles of the Code (the monitoring was conducted by the Bank of Russia), and by the results of this study that correlate with these data [27,28]. Almost all explanations lacked:

- clear indication of the Code provision to which the explanation relates;
- description of the context, circumstance, prerequisites showing why the company does not follow the Code;
- convincing and understandable explanations of the specific reasons for non-compliance with the Code;
- description of alternative risk reduction mechanisms used by the company;
- planned timeline for bringing corporate governance in line with the Code.

IV. Conclusions

Corporate governance is one of the most important factors in the investment attractiveness of companies. In their corporate practice, these companies, aimed at attracting long-term capital, adhere to internationally recognized standards that are trustworthy and understandable for all investors. The findings have demonstrated weak implementation of international corporate governance standards in the corporate practice of the overwhelming majority of Russian power generation companies. This is explained by the fact that these companies:

- Allow numerous violations of the criteria for compliance with the principles of the Code.
- Cannot compare with boards of directors of the largest companies in Europe, the United Kingdom and the United States in a number of key management indicators of Spencer Stuart, including evaluation of their performance and independent directors.
- Have low transparency of corporate reporting on the Transparency International criteria important for investors.
- Are not among companies with good corporate governance based on objective criteria, polls of the professional and expert communities of the Corporate Governance Index of Russia, based on the Good Governance Index, an international methodology adapted to Russian conditions.
- Treat formally the introduction of international "soft law" elements, including strengthening the expected rights of shareholders and applying the "comply or explain" principle that are recommended for countries with relatively weak legal and regulatory frameworks.

As a result, the weak implementation of modern international standards in the practice of corporate governance of Russian power generation companies does not contribute to an increase in their investment attractiveness.

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Modeling of Decreasing Short-term Marginal Costs and Corresponding Supply Functions of Condensing Power Plants at a Day-Ahead Electricity Market

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***Abstract* — The paper presents a calculation and an analysis of short-term marginal costs and corresponding supply functions of a condensing power plant. The calculation can be applied in power plant control systems or bidding support software to improve plant efficiency at the day-ahead market. A specific turbine is considered. Mathematical modeling is applied to determine first the short-term marginal costs and then the supply function of a price-taker based on the energy unit energy characteristics. The analysis shows that the short-term marginal costs function of a unit can decrease or can have decreasing segments. In this case, the supply function of a price-taker is not the same as the short-term marginal costs function. It is also shown that the supply function can be undefined for the output below the minimum output of the unit as well as within the range of decreasing short-term marginal costs. The form of the supply function does not correspond to the amount of units in operation.**

***Index terms* — thermal power plants; day-ahead market; supply function, marginal costs, market bidding**

I. Introduction

Relationship between marginal costs and supply functions of a price-taking producer is a key element of the modern market design. Generation is considered to be a competitive industry and according to the concept of perfectly competitive market, an individual supply function is the same as the marginal costs function under perfect competition. Otherwise, the producer can be considered to abuse market power. Some other often supposed properties of marginal costs functions are:

- the functions are defined from 0 to maximum capacity of the unit (or maximum output of the unit within the considered period);
- the functions are non-decreasing (marginal costs at higher output values cannot be lower than those at lower values);
- the functions do not depend on market clearing condition.

Many papers were published and models were developed based on these assumptions. Unfortunately, researchers pay very little attention to the assumptions themselves. Section II of the paper gives a literature review of how researchers deal with them.

Section III is focused on the calculation of a short-term supply function of an energy unit based on its energy characteristics. The turbine K-800-23,5-3 is considered in both single-boiler-single-turbine and two-boiler-single-turbine arrangements, and the former one operates within one-unit and four-unit power plants.

Section IV calculates supply functions based on the short-term marginal cost functions. Section V concludes the paper, describes some possible implications and suggests future study topics.

II. Literature review

The calculation of short-term marginal costs of real energy units or plants based on their measured characteristics is a rare focus of scientific research.

The author of [1], for example, states that the supply curve of a price-taking supplier is the same as his marginal costs curve. The author describes the supply function as a horizontal or slightly slanting line within the range of the unit installed capacity, and as a vertical line at the end of the unit installed capacity. The supply function itself is not calculated from the turbine and boiler characteristics.

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In [2], the supply function is introduced with reference to a typical short-term costs function, which is continuously differentiable and convex due to the law of diminishing marginal utility. The supply function is defined within the range from 0 to the maximum unit capacity, it is monotonically increasing and continuous.

In [3], the authors define marginal costs as a derivative of full costs function with respect to production value. In the examples, the marginal costs are given in cents per kWh irrespective of unit load factor (non-decreasing). The minimum output of units is not taken into account. In many other studies the cost functions of generators are assumed to be convex [4], [5].

For efficient market bidding support, the control systems must use the power plant optimization and unit energy characteristics. Unfortunately, very few researchers really do it. In [6]-[10], for example, the authors calculate costs based on the plant operating conditions, but they do not make a conclusion concerning supply functions. Therefore, calculation of supply functions of price-taking producers from their internal optimization and unit energy characteristics is an important but poorly investigated problem.

III. Short-term marginal costs

The scope of the paper is limited to the short-term marginal costs (STMC). These costs are typical of the decision whether or not to increase or decrease power output by 1 MW. The plant itself is constructed and the salary and taxes are already paid and are not taken into account. The costs that vary with the power output (mainly fuel cost) are under consideration. This approach is related to short-term markets (a day-ahead spot market and a balancing market).

A. STMC Functions of a Unit and their Domain of Definition

For most boilers used in Russia the minimum output is 40-60% of the installed capacity. Since the boilers cannot generate less than this value, the domain of definition of STMC functions starts at the minimum output and ends at the installed capacity of the unit for the single boiler-single turbine arrangement.

The dependence of the main steam flow rate (D_0, tons of steam per hour) on electrical output (N) of the turbine K-800-23,5-3 is best approximated with the equation taken from [11], (p. 273, Fig. 3.42.a)

$$D_0 = 3.271\ N - 81.379. \quad (1)$$

The dependence of the boiler fuel consumption (B, ton of fuel per ton of main steam) on the boiler load factor (U_b) is assumed to be

$$B = 0.191\ U_b^{-0{,}059}, \quad (2)$$

where U_b takes the values between 0.4 and 1. In the single-boiler-single-turbine arrangement

$$N = 800\ U_b. \quad (3)$$

From (1)-(3), hourly fuel costs F given fuel price (C_f, RUB/t) are

$$F = C_f D_0 B = C_f\,(0.927\ N^{0{,}941} - 23.058\ N^{-0{,}059}) \quad (4)$$

and the STMC function is

$$C_{stm1\text{-}1} = dF / dN = C_f\,(0.872\ N^{-0{,}059} - 1.360\ N^{-1{,}059}) \quad (5)$$

The calculated STMC function for the K-800-23,5-3 turbine in condensing mode is shown in Fig. 1. The minimum output is 40% and the maximum output is 100% of the installed capacity. The turbine energy characteristic is non-linear. The efficiency of the turbine rises with the output. The boiler efficiency also increases as it approaches the rated steam-output capacity (see, for example, [12], p. 197, Fig. 7.2.b). Therefore, the STMC function of the unit is decreasing. The fuel price is assumed to be C_f = 1200 RUB/t.

For the two-boiler-single-turbine arrangement, the STMC function domain of definition is larger and can start with 20-30% of the unit installed capacity because the boilers are put into operation one by one as the load increases. The discontinuity, however, arises at the point where one boiler operating at full capacity switches to two boilers operating at half capacity.

Let us consider the same turbine with two boilers of twice lower capacity but with the same characteristics, i.e. (1)-(2) are true. Instead of (3), we assume

$$N = 400\ U_b \quad (6)$$

for the case where one boiler is in operation and the other one is out of operation. Therefore, from (1)-(2) and (6) for the turbine load factor U_t = 0.2...0.5 the STMC function is

$$C_{stm2\text{-}1} = C_f\,(0.837\ N^{-0{,}059} - 1.306\ N^{-1{,}059}), \quad (7)$$

and for the turbine load factor U_t = 0.4...1 (both boilers are in operation and are loaded simultaneously, i.e. their output increases concurrently) STMC function is similar to (5)

$$C_{stm2\text{-}2} = C_f\,(0.872\ N^{-0{,}059} - 1.360\ N^{-1{,}059}). \quad (8)$$

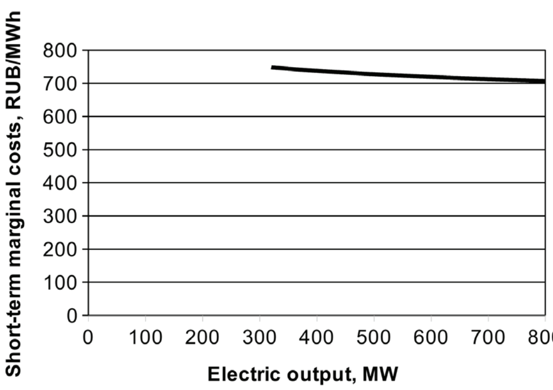

Fig. 1. The STMC function for the K-800-23,5-3 turbine in condensing mode.

The STMC function for the two-boiler-single-turbine arrangement is shown in Fig. 2. The minimum output is 20% and the maximum output is 100% of the installed capacity. It is worth noting that the capacity in the range of 40-50% can be maintained both by one or two boilers with different costs.

B. STMC Function of a Plant

As an example, we consider a plant with 4 similar single-boiler-single-turbine units described earlier. The minimum output of each unit is assumed to be 60% of the unit installed capacity. The STMC function is calculated assuming base-load condition of the plant. This means that no changes in the unit mix during operation are considered. Since the units are similar, four combinations of units involved are possible: one, two, three or four units in operation. The STMC function for n similar units involved is calculated as

$$C_{\text{stmn}} = C_f\,(0.872\,(N_p/n)^{-0.059} + 1.360\,(N_p/n)^{-1.059}), \quad (9)$$

where N_p – electric output of the power plant (units increase output simultaneously). The calculated STMC function for the power plant with four K-800-23,5-3 turbines in condensing mode is shown in Fig. 3. It is calculated assuming simultaneous loading of the units involved. Consecutive loading will cause a different result.

It is worthwhile to mention that the output ranges 0...480 MW and 800...960 MW go beyond the feasibility region for the plant under the assumptions given. On the other hand, the ranges 1440...1600 MW and 1920...2400 MW can be maintained by two different unit sets with different costs.

IV. STMC-based supply functions

Under perfect competition, any market participant is a price-taker, i.e. they are unable to influence the market clearing price. Generally, the supply curve of a generator is a set of points in the coordinate plane Price (Output), where each output value provides the maximum profit at a corresponding price.

If the STMC function is non-decreasing, as it is usually assumed, the Profit (Output) function at each price given has one extremum, and the supply function coincides with the STMC function. For decreasing STMC functions or those with decreasing segments, it is not the case. The full algorithm should be applied: assume a market price C_e, find the output value which provides maximum revenue minus fuel costs of the supplier, take the pair price-output as one point of the supply curve, and repeat the same procedure for other market prices assumed. The optimization criterion for the above described plant with n units (single-boiler-single-turbine arrangement, parallel loading) can be written as

$$\max\,(n, N_p) = (C_e\,N_p - F\,(n, N_p)), \quad (10)$$

where

$$F\,(n, N_p) = nC_f\,(0.927(N_p/n)^{0.941} - 23.058\,(N_p/n)^{-0.059}). \quad (11)$$

An additional constraint should be taken into account for decreasing STMC, i.e. at any point of the supply function the revenue cannot be less than the short-term costs. In other words, if the maximum revenue at a certain market price does not cover even the STMC, the price should be excluded from the feasible region of the supply function since the negative short-term profit does not encourage the producer to generate

$$\max\,(n, N_p) = (C_e\,N_p - F\,(n, N_p)) > 0. \quad (12)$$

For non-decreasing STMC, the condition is met naturally.

Figure 4 demonstrates the day-ahead market supply function of a power plant with one turbine K-800-23,5-3 by dotted line, and the plant with four turbines – by solid line. The function of the 4-unit plant is calculated under static condition, i.e. assuming the same power output and the same number of units involved. No starts or stops of units are considered. It is worth emphasizing that:

- the supply function consists of one vertical segment

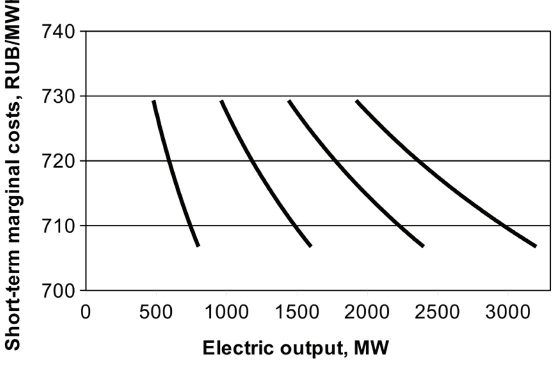

Fig. 2. The STMC function for the power plant with four K-800-23,5-3 turbines in condensing mode.

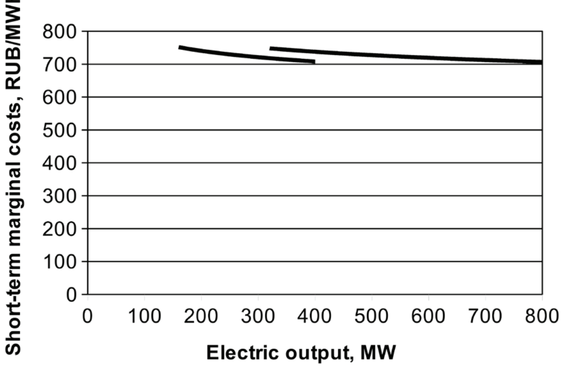

Fig. 3. The STMC function for the two boilers-single turbine arrangement.

both for 1-unit and 4-unit plant, the amount of segments does not depend on the amount of units;

- there are no horizontal or slanting lines or segments in both supply functions;
- both the 1-unit plant and the 4-unit plant do not generate at prices below 726.55 RUB/MWh and switch to maximum output at higher prices;
- the 4-unit plant never operates 1, 2 or 3 units and it is a perfectly competitive behavior. Both considered producers are never interested in operation with partial load.

Calculation of a dynamic supply function of a 4-unit plant requires additional assumptions: initial condition (n_0, N_{p0}), costs of a unit start (Fs) and the number of hours the started units will operate (t). The optimization is performed according to (10)-(12) for the same set of units and for the units that are switched on and off. Switching on units causes additional costs, and the optimization criterion (10) transforms to

$$\max(n, N_p) = (C_e N_p - F(n, N_p) - ((n - n_0)F_s) / t), \quad (13)$$

The dynamic supply function of the 4-unit plant assuming $n_0 = 1$, F_s = 5000 RUB, t = 8 hours is shown in Fig. 5.

The plant operates one or four units depending on the market price. Intermediary sets of 2 and 3 units in operation are never an optimal solution.

V. Conclusions and implications

The paper describes short-term marginal costs of an energy unit and calculates supply functions for the plants with one such a unit and four identical units. The study shows that:

- the short-term marginal costs function of a unit can be decreasing or can have decreasing segments;
- if the short-term marginal costs function is decreasing or has decreasing segments the corresponding supply function differs from the marginal costs function;
- for the range below the minimum output, the short-term supply function is undefined; it is also undefined within the range of decreasing short-term marginal costs;
- the amount of segments of supply function under perfect competition does not depend directly on the amount of units;
- dynamic short-term supply function of a plant differs from the static one because of initial condition, costs of a unit start and the number of hours the started unit is expected to run.

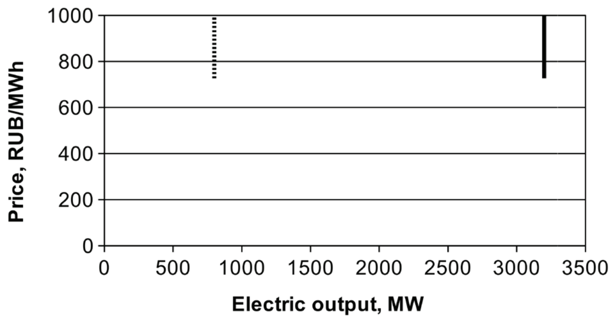

Fig. 4. The day-ahead spot market supply function of a power plant with one turbine (dotted line) and with four turbines (solid line) K-800-23,5-3.

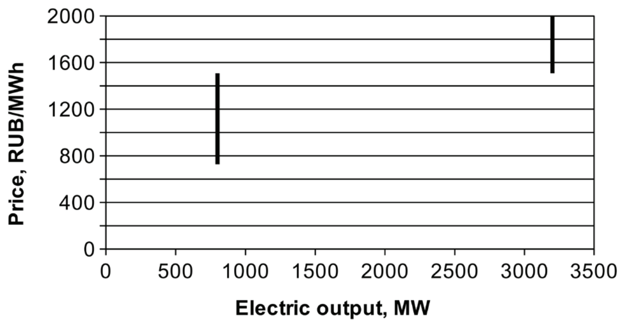

Fig. 5. The dynamic supply function of a 4-unit plant.

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Energy in the Context of Sustainable Development

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***Abstract* — The paper is concerned with the theoretical and methodological framework of the sustainable energy development and presents a notion of the sustainable energy development for a region. The methodology for a comprehensive assessment of the sustainable energy development is considered, and criteria for the sustainable energy development evaluation are identified. These criteria include the availability of resources, directions of social and economic development, demand for energy resources, and energy security. Based on this methodology a complex index is developed for estimation of the sustainable energy development, and for energy monitoring of the objects by an additive aggregation method. Based on the proposed index, the level of sustainable energy development of the Eurasian Economic Union (EEU) countries for 2016 was analyzed.**

***Index Terms* — energy, sustainable development concept, index of sustainable energy development**

I. Introduction

In September 2015, the UN members adopted the 2030 Agenda for Sustainable Development [2]. It contains a number of goals to eradicate poverty, preserve the resources of the planet and ensure prosperity for everybody. One of the goals is to provide general access to affordable, reliable, sustainable and modern energy sources for all. Each of the 17 goals contains a number of indicators to be reached within 15 years.

In the context of energy development until 2030, in particular, this entails:

- ensuring universal access to affordable, reliable and modern energy services;
- substantially increasing the share of renewable energy in the global energy mix;
- doubling the global rate of improvement in energy efficiency;
- enhancing international cooperation to facilitate the access to clean energy research and technology including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology;
- expanding infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries

II. The notion and the methodology to assess the sustainable energy development

There are a number of interpretations of this notion. We believe that the simplest and most accurate is the following: the sustainable energy development is the development of a self-regulating system of energy supply and energy consumption providing energy security, equally accessible satisfaction of energy needs and aspirations of all social strata at conservation of the environment.

This definition shows that sustainable energy development is a wider concept than energy security, since in addition to economic, technological and political factors it also includes ecological and social ones. Besides, energy supply and energy consumption are considered as interdependent parts of one system capable of self-regulation.

Moreover, sustainable development is subject to significant influence of a number of global energy risks, including:

- expansion of the energy system scale;
- threat of an imbalance between energy demand and supply, first of all, in terms of oil fuel;
- high level and instability of the world oil prices, the end of the cheap oil and gas era;
- disproportions in the world energy infrastructure because of hydrocarbon resources concentration in the areas remote from the main centers of consumption.

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90% of the world GDP is produced in the countries importing energy resources;

- risks of natural and technogenic catastrophes and system accidents, in part because of terrorist and subversive actions;
- negative environmental impact of energy;
- wide scale of energy poverty which means 2 billion people lacking the opportunity to use energy services in acceptable commercial and technological conditions.

The theory and practice of using the concept of sustainable development in energy have various approaches to understanding and methods to assess the condition of the given sector from the point of view of sustainable development. The issues of sustainable energy development were considered in the studies conducted by such experts as D. L. Green [2], I. Dincer [3], S. Connors [4], M.V. Myasnikovich [5], K. Prandecki [6], H. Rogall [7], G.W. Frey [8], etc. The methodologies for assessment of sustainable energy development were worked out by the World Energy Council [9] and Georgia Institute of Technology, USA [10].

At the same time, the existing approaches are focused on the determination of separate elements and factors characterizing sustainable energy development rather than on comprehensive consideration of this phenomenon.

Based on an analysis of the studies carried out by national and foreign scientists, we have identified the indicators of sustainable energy development.

All these factors can be divided into the following categories:

1) by the direction of influence – into external and internal ones;

2) by the sphere they relate to – into economic, technological, social, and ecological ones;

3) by the assessment principles of the sustainable energy development – into availability of resources, the directions of social and economic development, demand for energy resources, energy security.

A method to calculate the indicators of sustainable energy development is presented in Table 1.

The weight of the indicators is determined by the method of group expert assessment at direct estimation. At the same time, each expert establishes preferences of indicators when comparing all possible pairs, i.e. considering all possible pairs of indicators the expert establishes in each of them the reason, which, according to their opinion, exerts a greater influence on the result [12].

According to the Concept of sustainable development [1] and taking into account the specific features of energy distinguishing it from other industries (involvement in provision of the national security, mandatory generating capacity reserve, etc.), the economic, technological, social and ecological aspects are equivalent. In this regard, the identical weight equal to 0.25 is assigned to each of the factors.

In this stage, the index is calculated according to the following formula:

Table 1. A method to calculate the indicators characterizing sustainable energy development and their classificationt.

Factor	Indicator	Explanations concerning calculation
Economic	Availability of credit resources	Difference of 1 and the average interest rate for the credits and deposits of banks in national currency
	Share of energy in GDP	Ratio of the sum of the energy industries output to the total output
	Return on energy sales	Ratio of the sum of the energy industries gross profit to the total energy industries gross revenue
	Share of non-dominant energy resources in the total energy resources import	Difference of 1 and the share of the dominant energy resource in the total energy resources import
Technological	Share of own energy resources in the total energy consumption	Difference of 1 and the share of the imported energy resources in the total energy consumption
	Share of investment in energy	Ratio of investment into the energy industries to the total investment
	Energy-GDP ratio	Ratio of energy consumption to GDP
	Share of capacities not involved in the energy industry	Difference of 1 and the ratio of the sum of primary oil refining volume, electricity production, gas through gas pipelines transportation volume and oil through oil pipelines transportation volume converted to uniform measurement units, to the total capacities for primary oil refining, electricity generating capacities, gas pipelines capacity and oil pipelines capacity converted to uniform measurement units
Social	Employment rate	Difference of 1 and the share of the unemployed in the total labor force
	Education	The indicator of the same name from HDI is used [11]
	Availability of fuel and energy for population	Difference of 1 and the relation of fuel and energy expenses to the total expenses of households
	Population electrification rate	Share of the population having access to electricity
Ecological	Forest area level	Share of the forest area in the total land area of the country
	Life expectancy	The indicator of the same name from HDI is used [11]
	Coefficient of reducing energy resources consumption	Difference of 1 and the ratio of energy resources consumption for the reporting period to that in the previous year
	CO2 emissions caused by energy consumption per capita	Difference of 1 and volume of CO2 emissions from energy consumption divided by the population number

Table 2. Initial data and calculation results of the index of sustainable energy development for the EEU in 2016

Indicator	Weight	Belarus	Russia	Kazakhstan	Kyrgyzstan	Armenia
Group indicators characterizing economic factors	0,250	0,379	0,442	0,414	0,321	0,316
Availability of credit resources	0,285	0,739	0,866	0,834	0,778	0,840
Share of energy in GDP	0,194	0,115	0,226	0,134	0,048	0,046
Return on sales in energy	0,306	0,131	0,120	0,281	0,000	0,098
Share of non-dominant energy resources in the total energy resources import	0,215	0,492	0,535	0,298	0,419	0,174
Group indicators characterizing technological factors	0,250	0,418	0,616	0,642	0,651	0,509
Share of own energy resources in the total energy consumption	0,267	0,146	1,000	0,917	0,759	0,304
Share of investment in energy	0,276	0,174	0,281	0,343	0,191	0,076
Energy-GDP ratio	0,285	0,929	0,918	0,924	0,914	0,946
Share of capacities not involved in the energy industry	0,172	0,383	0,055	0,229	0,784	0,796
Group indicators characterizing social factors	0,250	0,923	0,908	0,925	0,900	0,826
Employment rate	0,210	0,950	0,945	0,950	0,923	0,824
Education	0,198	0,796	0,804	0,794	0,664	0,743
Availability of fuel and energy for population	0,372	0,929	0,887	0,935	0,956	0,769
Population electrification rate	0,220	1,000	1,000	1,000	0,998	1,000
Group indicators characterizing ecological factors	0,250	0,566	0,577	0,378	0,418	0,461
Forest area level	0,404	0,425	0,498	0,012	0,033	0,117
Life expectancy	0,138	0,792	0,773	0,763	0,781	0,844
Coefficient of reducing energy resources consumption	0,156	0,010	0,015	0,000	0,000	0,000
CO2 emissions from energy consumption per capita	0,302	0,939	0,883	0,887	0,983	0,982
Index of sustainable energy development	1,000	0,571	0,636	0,590	0,573	0,528

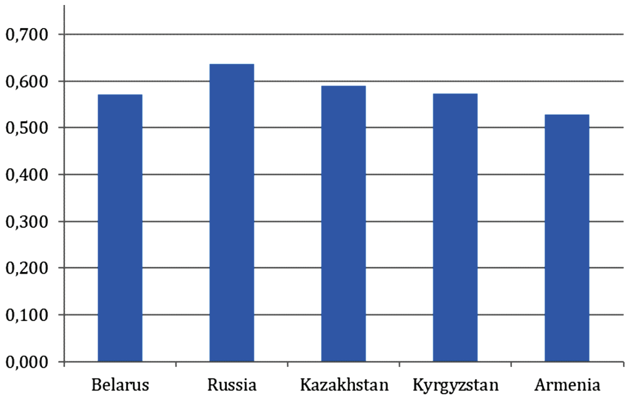

Fig. 1. Index of sustainable energy development for the EEU countries in 2016.

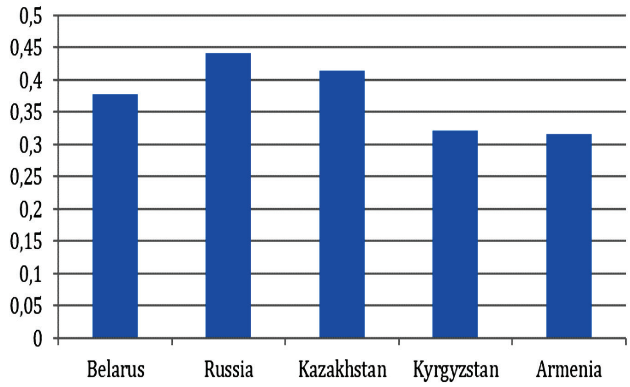

Fig 2. Group indicators characterizing economic factors of the EEU countries sustainable energy development in 2016.

$$I = \sum_{j=1}^{k} z_j \sum_{i=1}^{m} x_{ij} f_{ij},$$

where I – index of sustainable energy development; z_j – weight of j factor ; x_{ij}- weight of i indicator for j factor; f_{ij}- value of i indicator for j factor; k – number of factors; m–number of indicators.

III. Ranking of countries on the level of sustainable energy development

After calculation of the indices of sustainable energy development for different countries, they were ranked. The country with the highest value of the index is assigned 1.

On the basis of the given methodology, the index of sustainable energy development for the EEU (the Eurasian Economic Union) countries in 2016 was calculated (Table 2). Sources of information for calculating the index were the data of national statistics, the database of the International Energy Agency and the World Bank.

As evidenced by Figure 1, Russia is ranked first in the level of sustainable energy development in 2016, Kazakhstan is the second. Belarus and Kyrgyzstan are at a close level; Armenia is the last among the EEU countries. In general, for the EEU countries, except for Russia, the value of the index characterizing the level of sustainable energy development varies from 0.500 to 0.600, for Russia it exceeds 0.600.

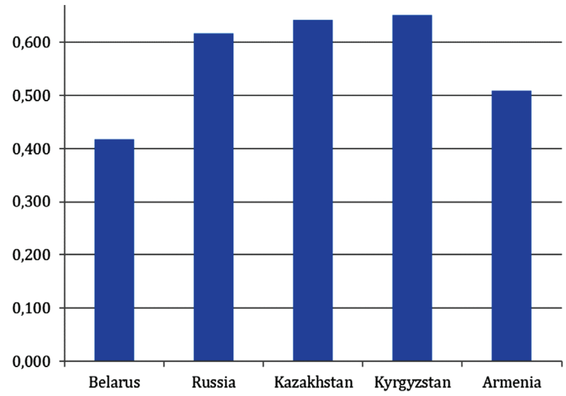

Fig 3. Group indicators characterizing technological factors of the EEU countries sustainable energy development in 2016.

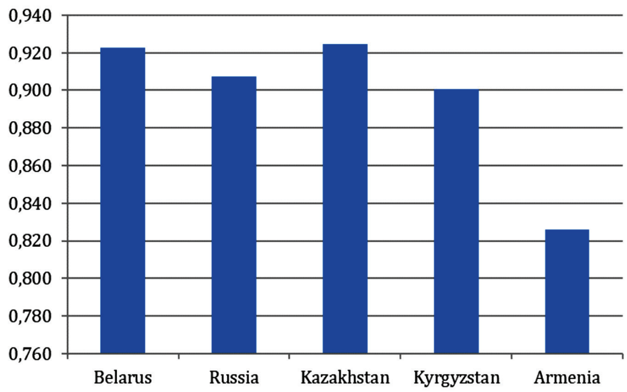

Fig. 4. Group indicators characterizing social factors of the EEU countries sustainable energy development in 2016.

Figure 2 shows the group indicator characterizing economic factors of the EEU countries sustainable energy development in 2016.

As seen from Figure 2, Russia is ranked first in the group indicator characterizing economic factors of sustainable energy development. This is caused, first of all, by the absence of imported energy resources in its energy consumption and the highest share of energy in GDP among the countries under analysis. Kazakhstan is the second. This country had the highest profitability of energy among

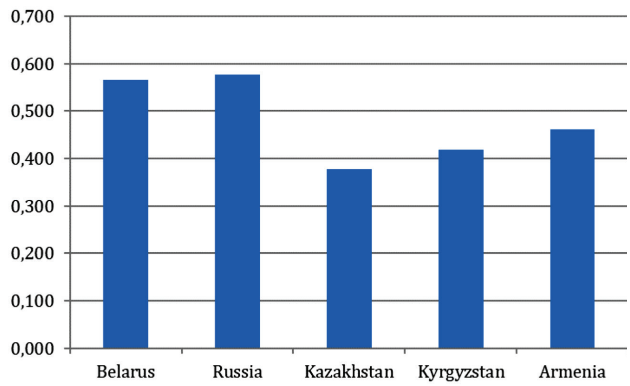

Fig. 5. Group indicators characterizing ecological factors of the EEU countries sustainable energy development in 2016.

the EEU countries and insignificant need to import energy resources. Armenia is ranked last owing to a low share of energy in GDP, low profitability and an insignificant share of non-dominant energy resources.

Figure 3 shows the group indicator characterizing technological factors of the EEU countries sustainable energy development in 2016.

As seen from Figure 3, Kyrgyzstan and Kazakhstan hold the leading positions in the group indicator characterizing technological factors of sustainable energy development, firstly - at the expense of a considerable amount of capacities that are not involved in the energy industry, secondly - at the expense of the share of own energy resources in the total energy consumption. Belarus is ranked last due to the lowest share of own energy resources in the total energy consumption.

Figure 4 shows the group indicator characterizing social factors of the EEU countries sustainable energy development in 2016.

As is demonstrated by Figure 4, Belarus and Kazakhstan are ranked first in the group indicator characterizing social factors of sustainable energy development in 2016, thanks to high employment rate and high availability of fuel and energy for the population. Armenia is the last due to a more considerable, than in the other examined countries, share of fuel and energy expenses in the total expenses of households.

Figure 5 shows the group indicator characterizing ecological factors of the EEU countries sustainable energy development in 2016.

It is obvious from Figure 5, that Belarus and Russia hold the leading position in the group indicator characterizing ecological factors of sustainable energy development in 2016 because of the high level of forest area in comparison with the other EEU countries and a positive coefficient of reducing energy resources consumption. Kazakhstan is ranked last in this group indicator due to the lowest level of forest area and life expectancy among the countries in question.

IV. Conclusion

Thus, Russia is ranked first in the level of sustainable energy development due to the high group indicators characterizing economic and ecological factors. Kazakhstan is the second because of high economic and social factors. Kyrgyzstan is the third owing to the high group indicator of technological factors and the average level of the other group indicators. Belarus is ranked fourth because of low group indicators characterizing economic and technological factors. Armenia is the last, although it has a high technological potential. Despite the differences in group indicators, all the countries have almost the same level of sustainable energy development, consequently, we can draw a conclusion that the coordinated economic policy and operation of the common energy market will allow the EEU countries to enrich each other with their experience in the improvement of various aspects of sustainable development.

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An Improved Technique For Identification Of Mathematical Models Of Thermal Power Equipment

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***Abstract* — The paper proposes an improved technique for identification of mathematical models of complex thermal power equipment. This integrated technique provides more effective detection of gross errors in measurements of control parameters applied for identification of a mathematical model of studied equipment, validation of the model, correction of errors in the model construction, and an increase in the identification accuracy. Additionally, the paper presents an original approach to considering the effect of a generating unit load on the internal relative efficiencies of turbine compartments, which can be applied to other adjusted coefficients of the mathematical model with nonlinear dependence on equipment operating conditions. The proposed technique was tested on a detailed mathematical model of a 225 MW generating unit. In the paper, the mathematical model identification problem is solved for the generating unit and an example of optimization calculation is demonstrated for the actual operating conditions to decrease specific fuel consumption for electricity generation.**

***Index Terms* — Identification of mathematical models, mathematical modeling, optimization of operating conditions, state estimation.**

I. Introduction

The improvement in the energy and cost efficiency of the main thermal power equipment at thermal power plants is surely a topical and noteworthy objective. It follows from the fact that the thermal power equipment forms the basis for Russia's electric power industry and consumes a considerable portion of mined fossil fuel and other resources [1].

The thermal power units (TPUs), such as boiler units and steam turbines, are technical systems with rather complex engineering flow diagrams, diverse elemental composition and operating conditions. Hence, the main instruments to study thermal power equipment are the methods of mathematical modeling and optimization of its flat diagrams and parameters.

Note that the equipment efficiency depends on its operating conditions and on-line control. The control efficiency of the main equipment of power plants can be improved by the operating personnel having a "feedback", i.e. the personnel should monitor changes in equipment parameters which are difficult or impossible to be metered directly (fuel consumption, generating unit efficiency, specific fuel consumption, etc.) with change in control actions [2].

The real state of thermal power equipment at thermal power plants (TPPs) is known to change in the process of operation, for example, salt accumulation in the turbine flow part, slagging of the heat-exchange surfaces of the boiler and regenerative heaters, and other changes which influence the equipment operation. Thus, the state estimation of main thermal power equipment is important for the on-line control of power plant operation [3].

II. Literature review

The foundations for application of the methods of mathematical modeling and optimization of thermal power equipment and thermal power plants were laid in the early studies by the researchers from Melentiev Energy Systems Institute. G.B. Levental and L.S. Popyrin dealt with optimization of continuous and discrete parameters of TPUs of different types and flow diagrams, presented automation principles of mathematical modeling of TPUs and described approaches to TPU optimization subject to initial information ambiguity [3, 4]. The methods of mathematical modeling of TPUs were developed by other Russian researchers: F.A. Vulman [5], A.A. Palagin [6], V.M. Borovikov [7].

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The state estimation and mathematical model identification were studied by A.Z. Gamm and his colleagues to calculate power system conditions in the context of measurement errors. Approaches to detection of gross errors in measurements (called "bad" data) that are based on the method of test equations are described in [8].

The state estimation and identification of the parameters of mathematical models are also applied to study pipeline systems. In his research, N.N. Novitsky comprehensively analyzes some state estimation problems and methods developed considering specific features of hydraulic circuits [9].

G.V. Nozdrenrko and G.D. Krokhin were the first to deal with these problems in thermal power industry [10, 11]. They proposed a technique for coordination of the heat and energy balance equations to solve the state estimation problems. However, these studies do not state and solve the identification problem of test parameters that cannot be measured directly, and do not examine the interrelation between the optimal solution and an error in measurements.

On the whole, by now a great number of technical and economic studies of energy (and other) facilities have been carried out using the methods of mathematical modeling and optimization. It is worth noting, however, that the indicated studies deal, as a rule, with relatively simple facilities and rather simplified mathematical models as objects of studies.

At present, of great interest are more complex energy facilities, such as combined-cycle gas turbines, multi-purpose thermal power plants producing both electric energy and synthetic liquid fuel, ultra-supercritical steam power plants and others. Usually, the optimization studies of such units involve the method of continuous enumeration of a predetermined set of flow diagrams and parameters [12-14]. The original methods of thermodynamic analysis are applied in combination with rather simple models to upgrade complex TPUs [15-16].

However, the insufficiently extensive use of effective mathematical modeling methods to control operating conditions of TPPs is explained by some difficulties. These are considerable complexity of mathematical models of current TPUs and the need to adjust these models to the actual equipment state changing over time.

Thus, the problems of state estimation of thermal power system operation and identification of mathematical model parameters have not been solved due to the complexity of objects of studies and their mathematical models, and the lack of effective methods, algorithms and computer programs to solve the required mathematical tasks. The results of solving the indicated problems are of importance in themselves and play a large part in solving the TPU control problems, e.g., optimal load distribution among the TPP units and optimal control of TPU and TPP operation.

An up-to-date generating unit installed at the Kharanor condensing power plant (Yasnogorsk settlement in the Trans-Baikal Territory) is taken as the object of the studies. It consists of the 225 MW steam turbine К-225-12,8-3Р with an intermediate steam superheat and the high pressure boiler ЕП-630-13,8-565 БТ with a steam capacity of 630 t/h. More detailed flow diagrams and mathematical models of the turbine and boiler are presented in [17].

The mathematical model of the generating unit was constructed using the software "System of the computer-based construction of programs" that was designed at Melentiev Energy Systems Institute [18]. The calculation scheme of the generating unit consists of 100 elements and 169 ties between them. The obtained mathematical model consists of 1154 input parameters and 1420 output parameters, 40 parameters of which are iteratively calculated and require an initial approximation to be specified.

This study is a continuation of research on identification of mathematical models of the main thermal power equipment at TPPs. The optimization problems were formulated, and some boiler and turbine units and other power equipment were calculated earlier in [18–25].

The software included some techniques designed for identification of mathematical models of energy equipment based on the measurements of the parameters (flow rates, temperatures, pressures, etc.) at different points of the flow diagrams of steam boilers and turbines that were taken during the tests of the studied equipment in several operating conditions [1, 2, 17, 25]. These techniques allow adjusting the mathematical model coefficients so that the results obtained using the mathematical model correspond most accurately to the actual equipment state, which ensures the validity of optimization solutions.

The application of these techniques made it possible to reveal their shortcomings which prevented us from successful identification of the studied equipment model. Firstly, the identification is successful, if there are no gross errors in the measurements of parameters. However, if the measurements in some of the considered operating conditions contain "bad" data with gross errors, the errors are redistributed among different measured parameters in one operating condition and, which is more important, among different conditions. Such redistribution does not enable the erroneous measurement to be uniquely determined and leads to incorrect solutions. Secondly, the indicated techniques do not take into account the errors of the mathematical model itself. The models of main thermal power equipment at TPPs are based on the standard calculation methods and do not always describe real processes sufficiently correctly. This introduces additional errors to be taken into consideration when solving the identification problem.

III. The methodology

In this study, we propose an improved identification technique. It is designed to develop a new integrated approach on the basis of the existing methods for identification of mathematical models. It consists of 3 stages to solve the above problems and improve the accuracy of the mathematical model identification.

The parameters of the mathematical model identification problem can be conventionally divided as follows: the parameters $x_з$ that are measured at the unit and are the input data for the mathematical model; the measured parameters yз that are the output data for the model and the parameters $x_н$ that are not measured at the real unit but are the input data for the model. The array of the adjusted coefficients θ of the mathematical model is selected individually for each model. They are applied to influence the physical processes that occur in the mathematical model elements. Usually, such parameters are the coefficients of thermal efficiency of the boiler heat transfer surfaces, the hydraulic resistances of heat exchangers, the internal relative efficiencies of turbine compartments, and others.

In the first stage of identification, the inaccurate measurements of the parameters are revealed and excluded from further calculations. The inaccurate measurements are the values of the measured parameters that exceed the required accuracy of the measuring instruments applied during the tests. Such measurements can be revealed by minimizing the coefficient ψ (equations 4, 5) for each operating condition of the considered equipment individually. The coefficient ψ corresponds to the absolute maximum relative deviation among the measured parameters. The mathematical statement of the first stage of the identification problem has the form:

$$\min_{X_H^i, X_3^i, \theta, \psi} \psi \quad (1)$$

subject to

$$H(y, x_H, x_3, \theta) = 0 \quad (2)$$

$$G(y, x_H, x_3, \theta) \geq 0 \quad (3)$$

$$x_{3j} - \psi \cdot \sqrt{\sigma_{xj}^2} \leq \overline{x_{3j}} \leq x_{3j} + \psi \cdot \sqrt{\sigma_{xj}^2} \quad (4)$$

$$y_{3k} - \psi \cdot \sqrt{\sigma_{yk}^2} \leq \overline{y_{3k}} \leq y_{3k} + \psi \cdot \sqrt{\sigma_{yk}^2} \quad (5)$$

where H is the function of the equality constraints which includes all equations of the mathematical model and its elements; G is the function of the inequality constraints which takes into account physical and operational limitations on the real equipment operation; ψ is the coefficient equal to the absolute maximum relative deviation of the parameters (the parameters calculated by the mathematical model are with the upper bar, the parameters obtained by measurements on the real equipment are without the bar); σx2, σy2 are the variances of the measurement errors of the vectors xз and yз, respectively.

The indicated variances are determined from the expression:

$$\sigma^2 = \left(\frac{XB \cdot \alpha}{3 \cdot 100} \right)^2 \quad (6)$$

where XB is the upper limit of the instrument range, α is the class of the instrument precision (in %).

The measurement errors in the controlled parameters of a generating unit follow the normal law of error distribution. According to the central limit theorem, the distribution law of the sum of independent random values with finite variances tends to the normal law at the increasing number of summands irrespective of their distribution law [26]. As applied to the measurements, this means that the normal distribution of random errors is typical of the case, where the measurement result is affected by a set of random disturbances and none of them is dominant. The so-called three-sigma rule is applied in this study, since the confidential probability in this case is equal to 0.997, which provides good grounds to state that all possible measurement errors distributed by the normal law do not practically exceed 3 sigma in the absolute value. In equations (4, 5, 10, 11), the multiplier equal to 3 is replaced with the minimized coefficient ψ initially assigned by a big number (50-100). This is necessary to consider both the errors of the applied measuring instruments and the errors of the calculation technique and mathematical models. In the process of the optimization calculation (1) this coefficient tends to the value of 3, however, in practice it often takes somewhat higher value. Thus, this technique enables us to determine an additional error caused by the imperfection of standard calculation methods and by the simplifications of the mathematical model of the studied TPU.

The erroneous measurements can be detected on the basis of the determined active constraint on the deviation of the measured parameter value from the calculated one. The value of the measurements in this constraint can be marked as erroneous and removed from further consideration. The studies have showed that such an approach provides more effective detection of errors in measurements and minimizes redistribution of erroneous measurements among the parameters in different conditions.

In the second stage of the improved identification technique, the mathematical model of the studied equipment is tested for the errors in modeling. The optimization problem is similar to the problem solved in the first stage, only it is solved for all considered conditions jointly.

The study has indicated that solving this problem makes it possible to reveal that the mathematical model provides an incorrect description of the processes taking place in the generating unit. If there is a considerable deviation of parameters from measurements in different conditions of equipment operation, this is indicative of the absence of the required coefficient in the list of those to be specified or the inaccuracy of mathematical model construction, or it may be necessary to take into account negligible heat carrier flows neglected in the stage of mathematical model construction.

In the third stage of the mathematical model identification the following optimization problem is solved

$$\min_{X_H^i, X_3^i, \theta} f(y^i, x_H^i, x_3^i, \theta) \tag{7}$$

subject to:

$$H(y^i, x_H^i, x_3^i, \theta) = 0 \tag{8}$$

$$G(y^i, x_H^i, x_3^i, \theta) \geq 0 \tag{9}$$

$$x_{3j}^i - \psi \cdot \sqrt{\sigma_{xj}^2} \leq \overline{x_{3j}^i} \leq x_{3j}^i + \psi \cdot \sqrt{\sigma_{xj}^2} \tag{10}$$

$$y_{3k}^i - \psi \cdot \sqrt{\sigma_{yk}^2} \leq \overline{y_{3k}^i} \leq y_{3k}^i + \psi \cdot \sqrt{\sigma_{yk}^2} \tag{11}$$

$$f = \sum_{i=1}^{R} \left[\sum_{j=1}^{N} \frac{\left(x_{3j}^i - \overline{x_{3j}^i}\right)^2}{\sigma_{xj}^2} + \sum_{k=1}^{M} \frac{\left(y_{3k}^i - \overline{y_{3k}^i}\right)^2}{\sigma_{yk}^2} \right], \tag{12}$$

where f is the objective function that takes into account the deviations of all parameters calculated by the mathematical model (with the upper bar) from the measurements taken at the real equipment (without the bar), given the precision of measuring instruments used during the tests of the studied equipment; R is the number of calculated conditions; N is the dimension of the vector x_3; M is the dimension of the vector y_3.

IV. Results

The paper presents the calculation results obtained using the proposed improved technique for identification of the mathematical model of thermal power equipment with respect to the above-described generating unit.

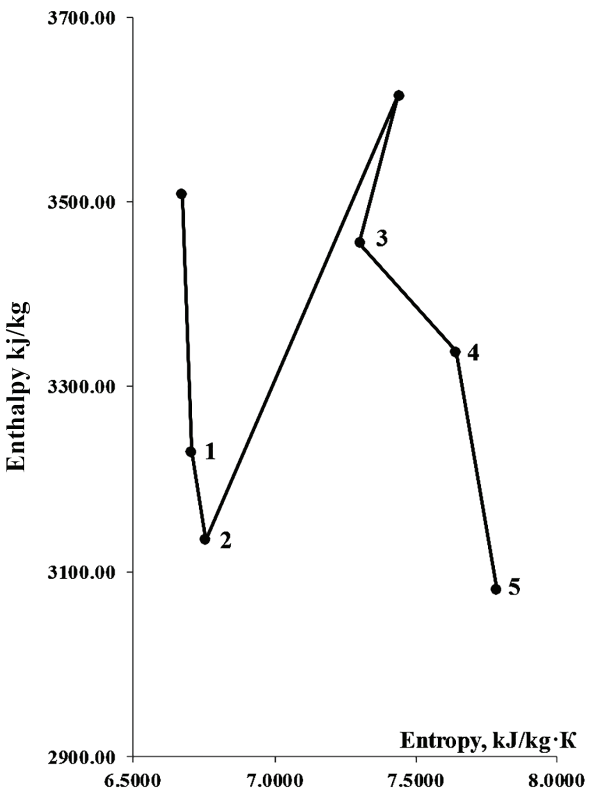

Fig 1. Steam expansion process in the first turbine compartments in the h,s-diagram.

The values of the measured parameters at the control points of the flow diagram that are necessary for the mathematical model identification were taken from the sensor readings provided by the engineering personnel of the power plant. The precision class of the applied instruments is 1% for the instruments measuring pressure, 2% for the instruments measuring temperature, 1.5% for the instruments measuring flow rate. The calculations were performed for several selected operating conditions of the generating unit. In one of the conditions, the feed water bypassed a group of high pressure heaters in the turbine. Each condition contained 55 measured values of the parameters at different points of the flow diagram.

The coefficient ψ was minimized in the first stage of the identification procedure. The optimization problem was formulated for each condition individually. The number of optimized parameters was 67, and the total number of inequality constraints was 234. The minimized coefficient ψ considerably exceeded the threshold value equal to three.

In this stage, three measurements in two conditions were revealed to contain gross errors. The first parameter, the steam pressure at the inlet of the 6th turbine compartment, was removed from the calculation in two conditions, and the steam temperature at the outlet from the 3rd turbine compartment-only in one condition.

Validity of the removal of the steam temperature measurement at the outlet from the 3rd turbine compartment can be proved using the *h,s*-diagram of the steam expansion process in the first five compartments for the considered condition which was developed on the basis of the measured values of the parameters. The diagram is presented in Fig. 1. The figures on the plot indicate the number of the turbine compartment with the steam temperature measurement at the outlet. The internal relative efficiency of the turbine compartment above unity (slope to the entropy decrease) is thermodynamically impossible. Consequently, this measurement in the second condition is inaccurate and must be excluded from further calculations.

The steam pressure measurement at the 6th turbine compartment inlet that corresponds to the pressure of steam extraction for the low pressure regenerative heater LPH-3 was tested in a similar way. Based on the measurements it is approximately equal to 2.6 kgf/cm^2. For the given pressure, the saturation temperature is 128 °C. At the same time, the water temperature measurement at the LPH-3 outlet is approximately 140 °C. It is evident that the water flowing through this regenerative heater cannot be heated up to the saturation temperature at the specified pressure. Thus, this measurement must be removed from further calculations.

After removal of the inaccurate measurements, the mathematical model of the studied generating unit was tested for available errors in modeling in the second stage. The optimization problem statement is similar to the statement of the problem solved in the first stage, only it was solved for all considered conditions jointly. The number of optimized parameters in this problem was 82, and the total number of inequality constraints was 605.

An original idea to take into account the effect of change in turbine capacity (or steam flow rate at the turbine inlet) on the efficiency of its compartments was tested in this stage. The internal relative efficiency of turbine compartments is known to be variable and changes its value depending on the turbine load. For example, in the operating conditions close to normal ones it will be higher than in the conditions with a higher or lower load.

A turbine compartment is a group of stages between the steam extractions. The mathematical model of the turbine compartment consists of several equations (13-16). The main calculated parameters of the compartment are the steam pressure P_1 at the inlet, the steam enthalpy H2 at the outlet and the mechanical output N_M of the compartment

The pressure P_1 is determined by the known Stodola-Vlugel formula, where index 1 indicates the parameter values at the compartment inlet, and index 2 – at the outlet. The steam parameters in the nominal (or in some other representative) condition are denoted by the asterisk.

$$P_1 = \sqrt{\frac{G^2 \cdot P_1 \cdot V_1 \cdot \left(P_1^2 - P_2^2\right)}{G^{*2} \cdot P_1^* \cdot V_1^*} + P_2^2} \quad (13)$$

where P is the steam pressure; G is the steam flow rate through the compartment; V is the specific steam volume.

The enthalpy H_2 is determined by the ideal heat drop, given the internal relative efficiency of the turbine cylinder. The impact of the steam moisture degree on the compartment efficiency reduction is also taken into consideration in the turbine compartments with wet steam formation, where P is the steam pressure; G is the steam flow rate through the compartment; V is the specific steam volume.

The enthalpy H_2 is determined by the ideal heat drop, given the internal relative efficiency of the turbine cylinder. The impact of the steam moisture degree on the compartment efficiency reduction is also taken into consideration in the turbine compartments with wet steam formation.

$$H_2 = H_1 - \left(H_1 - H_2^i\right) \cdot \eta_i \quad (14)$$

where H_1 is the steam enthalpy before the compartment; $H_2{}^i$ is the steam enthalpy at the end of ideal expansion up to the pressure P_2; η_i is the internal relative efficiency.

$$N_M = G \cdot \left(H_1 - H_2\right) \cdot \eta_м \quad (15)$$

where $\eta_м$ is the mechanical compartment efficiency.

As distinct from all previous studies, the optimized internal relative efficiencies of the turbine compartments were replaced with the quadratic functions, where the ratio of the actual steam flow rate (G) through the compartment to the nominal flow rate (G^*) was used as a variable. The coefficients A, B, C in equation (16) are common for each turbine cylinder (HPC, IPC, LPC), but the coefficients η_i are determined for each compartment depending on the turbine load in different operating conditions

$$\eta_i = A \cdot \left(\frac{G}{G^*}\right)^2 + B \cdot \left(\frac{G}{G^*}\right) + C \quad (16)$$

An example of the obtained relationship between the internal relative efficiencies of two first turbine compartments and the turbine load is given in Fig. 2.

Moreover, the calculations of the second identification stage showed that some calculated parameters in the deaerator significantly deviated from the measurements. Therefore, it was decided to change the mathematical model of this element by replacing the optimized steam throttling coefficient in the deaerator with the quadratic function of the form $k_Д = A \cdot x^2 + B \cdot x + C$, where x is the live steam flow rate at the turbine inlet that characterizes the turbine capacity; A, B, C are the new optimized coefficients. This change made it possible to adjust the mathematical model of the deaerator in terms of the impact of change in the turbine capacity in different operating conditions, which somewhat improved the accuracy of the generating unit model identification. The indicated changes in the second stage of the identification allowed minimizing the objective function (the coefficient ψ) to the value equal to 3.81, which somewhat exceeded the threshold value but was reasonable.

The optimization problem (equations 7-12) was solved in the third stage. There were 81 optimized parameters, and the total number of inequality constraints was 605. It is worth noting, that the coefficient ψ minimized in the first and second identification stages was excluded from the list of optimized coefficients and fixed. The third identification stage was needed to achieve the maximum possible closeness between the real equipment operation and the calculations on the mathematical model. Objective

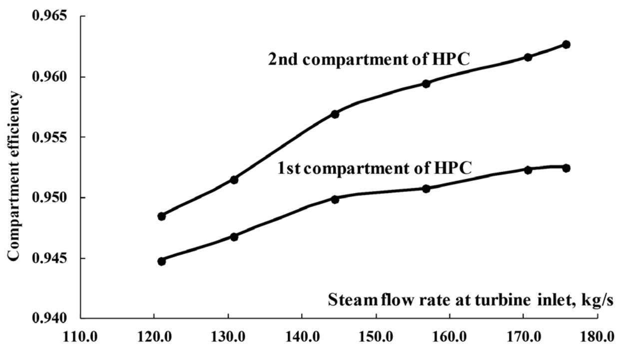

Fig. 2. Relationship between the internal relative efficiencies of two first compartments and load of the turbine

Table 1. Example of generating unit operating conditions optimization

No.	Parameter, measurement unit	Actual condition	Optimal condition
1	Consumption of fuel burnt in boiler, kg/s	34.22	33.38
2	Air-fuel ratio in boiler furnace	1.31	1.205
3	Enthalpy reduction in 1st injection, kcal/kg	8.54	1.27
4	Enthalpy reduction in 2nd injection, kcal/kg	7.29	0.37
5	Enthalpy reduction in 3rd injection, kcal/kg	2.54	2.45
6	Enthalpy reduction in LP injection, kcal/kg	27.93	3.61
7	Feed water pump head, kgf/cm2	168.95	179.11
8	Control action on reheat steam flow rate through 1st stage steam superheater, kgf/cm2	0.673	0.31
9	Water flow rate at condenser inlet, kg/s	10419	9825
10	Specific consumption of coal equivalent for power generation (gross), gce/kWh	305.01	297.89
11	Specific consumption of coal equivalent for power generation (net), gce/kWh	333.39	319.86
12	Gross generating unit efficiency	40.28	41.24
13	Net generating unit efficiency	36.85	38.41

function (12) in this case in contrast to the coefficient ψ was the sum of squared residuals of the parameters in all considered operating conditions of equipment. Correspondingly, in the third stage, we can achieve a reduction in all relative residuals of measured parameters, not only the maximum residual as in the first and second stages. After the identification was completed, the adjusted coefficients θ of the mathematical model were fixed and could not be changed.

Additionally, identification of the mathematical model of the studied equipment allows solving some important operational problems, such as state estimation of thermal power equipment or optimization calculations of flow diagrams and parameters of the studied thermal power plant equipment to improve its efficiency.

The optimization calculation on the identified mathematical model of the generating unit can be presented as an example. Consumption of the fuel burnt in the boiler unit was used as an objective function. An array of inequality constraints consisted of both physical constraints (on the temperature of pipe metal, the mechanical metal stress, the non-negativity of steam flow rates, etc.) and operating constraints (on the temperature of primary and secondary steam, the pressure in the condenser, the turbine capacity). Table 1 presents the values of the optimized parameters (lines 1-9), and the values of the generating unit efficiency (lines 10-13) in one of the considered conditions and in the calculated optimal condition.

The Table shows that changes in the operating parameters of the generating unit make it possible to considerably decrease the quantity of fuel burnt in the boiler with the same power output, which somewhat improves the efficiency of considered generating unit.

V. Conclusions

The paper proposes an improved technique for identification of mathematical models of complex thermal power equipment. The calculations indicate that the technique: a) more effectively detects gross errors in measurements of the control parameters applied for identification of the mathematical model of the studied equipment, assesses its correctness, b) corrects errors in the mathematical model construction and c) improves the identification accuracy.

Moreover, the paper presents an original approach to considering the turbine load impact on the internal relative efficiencies of turbine compartments, which can be applied to other adjusted coefficients of the mathematical model with the nonlinear dependence on the equipment operating condition. As a result, the adjustment accuracy of the mathematical models of TPUs is improved.

The improved technique for identification of mathematical models was tested on the detailed mathematical model of the advanced 225 MW generating unit. The study focused on the identification of a mathematical model of a generating unit and an example of optimization calculation of actual operating condition to decrease specific fuel consumption for power generation.

The mathematical model identification is important and plays an important part in TPU control, including the optimal load distribution among the TPP units and the optimal control of TPU and TPP operation.

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A Computing System for Processing the Interstate Power Grid Data

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***Abstract* – The paper presents a Data Processing and Geo-information Computing System (DPGICS) intended to study and forecast the expansion of interstate power grids. We propose an original technology for data storage in an object-oriented database, and a technology for data processing and representation using user-friendly interface. An example is given to demonstrate the DPGICS applied to visualize energy data on maps, and to form aggregated tables with the results obtained using the ORIRES optimization model being part of DPGICS.**

***Index Terms*: geo-information system, optimization model, data processing, object database, power plant, power system, interstate power interconnection.**

I. Introduction

Establishment of interstate power grids (IPGs) is a global trend in the world electric power development. This process involves proving their effectiveness, projecting their further expansion, meeting the economic interests, complying with technical standards of the member countries, and considering many other aspects.

Investigations of such kind require big preliminary work on collection and analysis of a huge amount of data (technical, economic, ecological), complex technical and economic calculations, significant intellectual and information resources. Without developed problem-oriented software reflecting the specificity of the given subject area, investigations take a great deal of time and effort. Multi-aspect results of calculations can hardly be perceived by experts without a convenient user interface for data processing and presentation.

Currently, methods of processing and analysis of large amounts of data are studied by many researchers from different countries in various science areas: computer science, mathematics, power engineering and others. In Russia, the well-known studies in the area of data processing were conducted by A.A. Barsegyan, M.S. Kupriyanov, V.V. Stepanenko and I.I. Holod – "The Data Analysis Technologies. OLAP Data Mining" [1], V.A. Duke – "Telemedicine", "Data Mining" [2]. The foreign reserachers involved in the study of information technologies for intellectual data processing (Data Mining) are Jiwei Han and Philip S. Yu (The Data Mining Group, University of Illinois, USA), and Charu Aggarwal (IBM, USA) to name but a few.

Many researchers and international organizations investigate the Interstate Power Grids. These are Global Energy Interconnection Development and Cooperation Organization (GEIDCO, China), Asia Pacific Energy Research Centre (APERC), United Nations Economic and Social Commission for Asia and the Pacific (UN ESCAP), Renewable Energy Institute (Japan) [3], Korea Electrotechnology Research Institute (South Korea) [4-5], China Electric Power Planning and Engineering Institute (China), Economy and Technology Research Institute (China), Mongolia Energy Regulatory Commission [6] and others. A lot of universal software was developed. In most cases, relational databases are used for energy data storage. OLAP, Data Mining and others methods are used to process multidimensional data sets. The proposed methods of data storing and processing are intended for universal solutions, but they do not meet the goals set.

Comprehensive research of transmission lines and electricity generation is indispensable for the IPG system expansion and substantiation [7]. Therefore, an optimization model is used to study the IPG expansion, choose the optimal commissioning of power plants and transmission lines to cover the growing load in the target year [8]. We collect and process huge arrays of data for this model. However, most energy databases are not publicly available for research in this domain. We needed software with convenient user interface to work with the optimization model and to analyze the results obtained.

Herewith, the IPG and electric power systems (EPSs)

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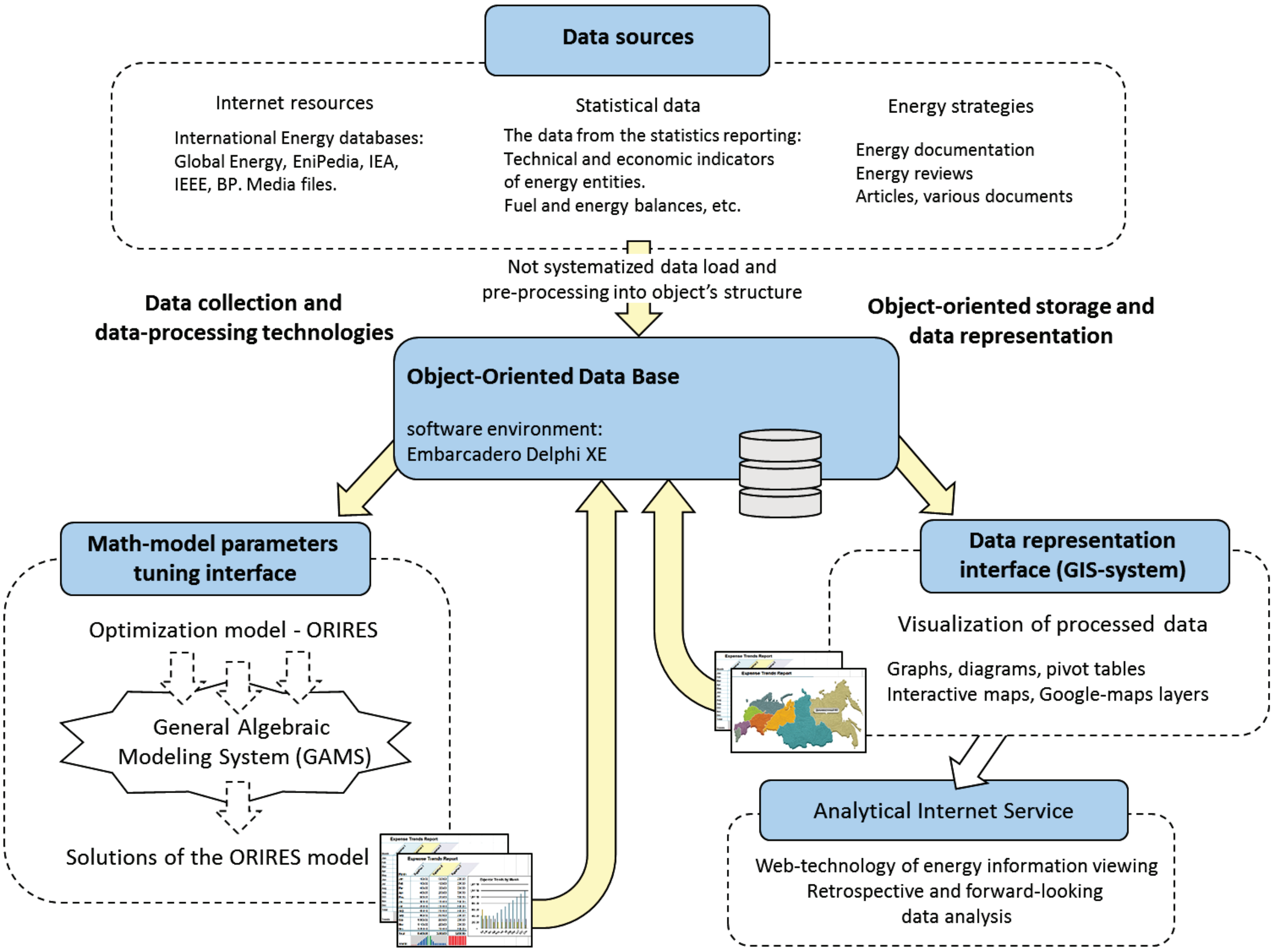

Fig. 1. DPGICS functional blocks.

being their parts are modeled as structurally complex power entities (EPS, power plants, transmission lines) that are described by a big set of diverse dynamically varying parameters. With no problem-oriented software, the above problems have been long solved by labor-consuming calculations done practically "manually" using the Microsoft Excel. Therefore, there emerged a necessity to create and use the software for complex scientific investigations aimed at designing and projecting the IPG expansion.

The accomplishment of the set goal required a technology (method) for non-structured data collection and processing. Such data involve isolated energy and power-related information collected from various sources, and algorithms for its conversion and storage. It was also necessary to integrate the collected information resources into a geo-information computing system with an object-oriented database.

We know only several close functional software analogs. These are the Asia Pacific Energy Portal by UN ESCAP [9], the Energy GIS-system developed by GEIDCO (China) [10], and APERC Energy Data Network Service [11]. All of them contain a considerable amount of data on power plants and transmission lines worldwide.

The above analogs, however, have no computing part, and in the context of this paper, may be termed only as geo-information systems. We have been developing both the Data Processing and Geo-Information Computing System in one software-product. Our software, besides visualizing the power data, is intended for energy experts (our users) to conduct optimization calculations and to construct well-developed projections for the IPG development, by using mathematical optimization model.

II. The Data Processing and Geo-Information System Issues

A research team of the Melentiev Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences (ESI SB RAS) investigates the formation of interstate power grids. To boost the efficiency and quality of this research, we have developed the Data Processing and Geo-Information Computing System (DPGICS).

Figure 1 presents the main DPGICS structural-functional blocks and the data flows among them.

The functions of the Data Sources block are to collect data from heterogeneous information resources and to convert them to a uniform database structure used in the DPGICS. To store the information in a uniform structure within the DPGICS, we have developed an Object-Oriented Database. The data represent a system or a set of files in a special machine-readable format containing the parameters for the database object, its text and numerical values with special separators.

The next DPGICS functional block is intended to operate the ORIRES optimization model. The DPGICS interface allows experts to adjust and vary the ORIRES input parameters, the number of nodes and constraints, to run the "optimizer," and to generate the final set of tables with the optimal solution results. Further, the obtained set of tables determining a certain scenario of the IPG development for the target year is also stored in the DPGICS data structure.

To visually represent and analyze the information from the object-oriented database in the DPGICS, we have developed the Data Representation Interface block. We use the maps built by the free Google Maps Application Program Interface (Google API) as a background on which semi-transparent layers representing various power parameters are imposed. This interface allows scaling the map and analyzing the trends of parameter variations over different time periods, for example, over the last 20 years. The user can see these trends on the built maps, and in plots or diagrams.

Further, we developed and run a special DPGICS block – Analytical Internet Service [12] to represent the investigation results on the Internet. At a request, the DPGICS-generated maps, tables, and diagrams (keeping some dynamic functions implemented through web programming) are exported into this web application. For example, the DPGICS web interface users can also analyze the power parameter variation dynamics on the maps for different years (only as simple examples with animation of these trends).

The DPGICS implementation involved the following technologies.

We used the Embarcadero Delphi XE, API Google Maps, SHP and XML files containing geographical and other energy & power data as a basis for construction of the DPGICS and the object-oriented database. To create the DPGICS web-interface, we applied the web technologies based on PHP, Ajax, Jquery, JavaScript, MySQL, and Bootstrap. The ORIRES optimization model is represented by a set of mathematical formulas and equations solved in the DPGICS through the general algebraic modeling system. The model parameters are set and written in/from the object-oriented database for their further processing and presenting in the DPGICS table-graphic interface.

The information technologies applied in the DPGICS development, allow full implementation of the stated problems. The under-construction DPGICS integrates in itself algorithms for collecting/loading and processing semi-structured data (in the stage of their loading and re-structuring into an object form), and also technologies for graphical and cartographical data display. To present the final information in the cartographical interface, we use the registered layers of GIS-maps with the basic components for the power infrastructure of the countries and interconnections.

Table 1. A fragment of data on the selected OODB object.

Parameter name	Parameter value
ID	170710110631
year_s	1980
lat	36.47750000
long	127.48083333
country	Korea__South
district	Chungcheongbuk-do
name	Daecheong_Powerplant
type_st	hydro
add_files	inet_170710110631.docx
n_rasp	90.00|90.00|90.00|90.00|90.00|90.00|90.00|90.00|90.0 0|90.00|90.00 …
w_gen	240000.00|240000.00|240000.00|240000.00|240000.0 0|240000.00|240000.00 …
	…

III. Technology for the DPGICS data storage and presentation

As noted above, to store and process energy & power data, we have developed an object-oriented database (thereinafter – OODB) within DPGICS. The idea of the technology for data storage in the OODB is that all the information loaded/written in the system is structured through different program algorithms (it depends on a certain resource) and stored in the form of unique database objects describing power parameters of the real world entities. Forms of the OODB objects may be various and independent: power plants, transmission lines, region, country, power interconnection [12], and others.

Each OODB object represents a record containing an object unique identifier, a set of parameters describing it, and the values of each parameter in a text or numerical form, stored by year, month, day, etc.

The content of database objects is represented in CIS interface by dynamic editable tables. The table contains object parameters and its values, see Table I. The edited values are automatically recorded in an object form.

Further, a separate file is opened in a simple text editor, where user can see a fragment of parameters and values of the selected object, written in a special format. In the example above, there is a fragment of the data for the Daecheong Power Plant (South Korea EPS). The OODB stores about 100 power objects belonging to South Korea

EPS. Here we can see:

1. Text parameters of the object, i.e. the unique identifier (ID), year when the data collection started (year_s), object name (name), latitude and longitude coordinates,

a region (country), a province (district), power plant/capacity type (type_st), additional files describing the object (add_file). There can also be photos, videos, etc. Some of them can be indicated as key field for aggregation, for example, one can aggregate objects by “type_st”, or by “country” etc.

2. Numerical parameters of the object, i.e. installed capacity of power plant for every year, starting in 1980 (n_rasp, in MW), total electricity generation per year (w_gen, in MWh) and any others.

This list of parameters is length unlimited and may occupy several pages. The inner structure of the OODB files is not only convenient for machine processing but also is clear to a person (human). The data structure universality and simplicity make them practically independent of the programmers.

The information storage technology in the object form has an advantage over relational databases for the following reasons.

- The number of records and their length in our data structure are not limited. Accordingly, one can store an infinite number of the object parameters and their output values in one string, for example, hourly load within an entire year or a period of years without creating additional relational tables.
- One may use a free type/format of parameter values, viz., fractional, integer, or text, stored in an unlimited range of values. For example, frequent change in the names of power entities by year can be presented in the form of the Name parameter, whose text values are written in one string with special separators. The values for such a parameter can be taken from the OODB for any requested year, or for some years, for example, to see the name change trend.
- There is no need for a large number of relational tables and indices when operating with big lists of different types of objects unconnected with one another.
- The necessity to compactly present comprehensive information on a power entity in one special-format file. Such a presentation provides confidence in the data integrity and excludes potential losses and data originating at complex SQL-queries "collecting" values for one or several entities from various relational tables.

We have developed program algorithms for data input/output from the OODB by using graphic and cartographic data representation. We developed program procedures to verify the data and check them for integrity. To exclude duplication of the objects collected from various sources, we have developed algorithms for comparison that employ simple methods of semantic and syntactic text analysis. It is also possible to visually search for the facilities (in the case of power plants) by geographical coordinates on the Google Maps: we revealed the cases, when the power plant geographical coordinates were intentionally or accidentally "shifted" a few kilometers away from their real location. Most major objects in the OODB have real geographical coordinates and can be presented on the maps through the DPGICS cartographic interface.

Quality research requires maximum comprehensive information on the investigated entities or processes. In particular, to determine the current state of a power system in a region, it is necessary to have the information on the installed capacities of the given EPS. When searching and obtaining such information, a researcher faces subjective and objective difficulties, because information sources are, as a rule, separated and located on various Internet

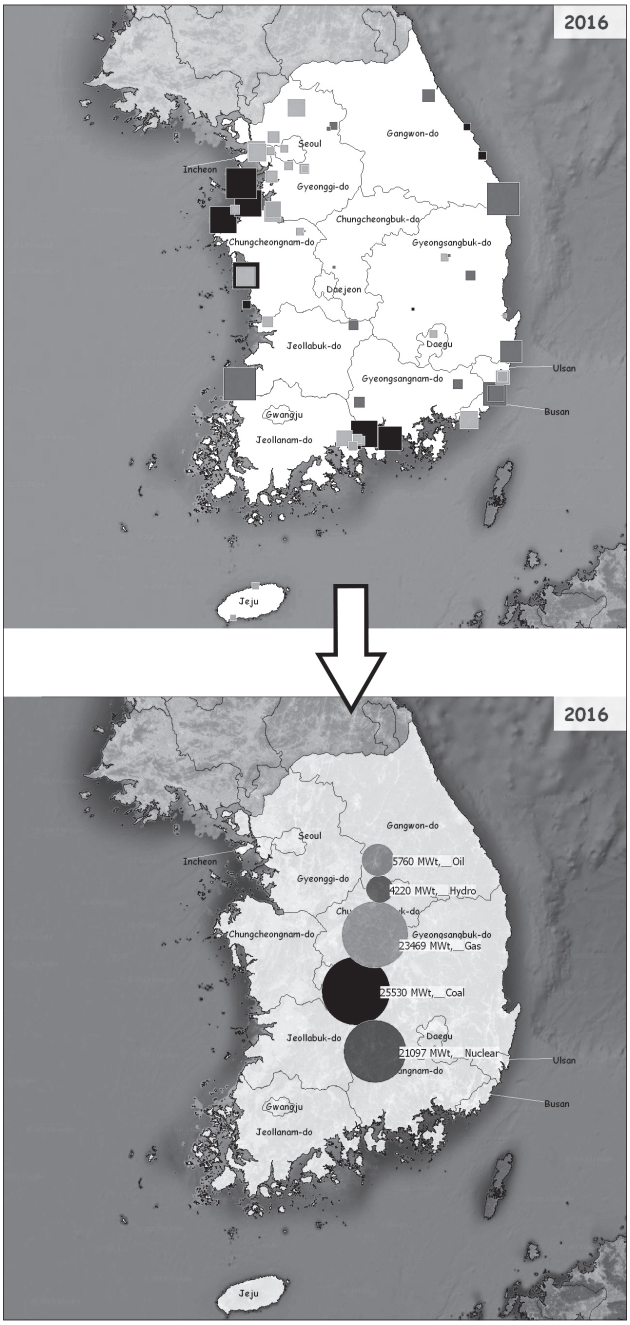

Fig. 2. Aggregation of power plant installed capacities in South Korea.

resources. To cope with this problem, we have developed a semi-automated method to collect/download semi-structured information from various sources and to convert it in an object structure with its subsequent verification and analysis. Each algorithm for downloading and converting the information in the OODB depends on certain types of data sources. We use combined (manual and semi-automatic) processing algorithms for data download such as parsing of MS Excel statistic tables, or automatic download of the entire data spreadsheets from various public energy databases like EnergyStorageExchange.org, EniPedia.org etc.

To load a great volume of the information presented in ontology form at DBPedia/EniPedia.org, for example, we have developed a program algorithm implementing the syntactic analysis of the XML-format data exported from the above Internet resource, and allocating the parameters of power plants and their values into the OODB structure [13]. To verify the objects downloaded from various sources in the DPGICS, we use simple algorithms to compare the obtained new objects with those already existing in the OODB.

This operation is executed for each new class of objects only once. In the event that there is updated information on the objects existing in the database (for example, new statistics for the current year), each program algorithm automatically distributes new values to the corresponding cells in the database structure. Based on the algorithms developed for various sources, we form and enlarge the OODB with unique information collected in a uniform structure whose usage expands manifold possibilities and enhances the quality of scientific research.

Further, the data from the OODB are processed through a convenient "query designer interface" (we have developed an add-in for SQL that uses the certain terms for convenient work of energy experts). This "query designer" allows us to extract object parameters, classify them, sample, and aggregate. The objects possess an expansive set of parameters that can be added when using the OODB. For power plants, in particular, we added the parameters for their cartographic binding and possibility of presentation on the DPGICS maps [14-15].

With the information on exact location of entities, the data can be aggregated at various levels, which opens up the possibilities for scaling the ORIRES model, i.e., for creating different levels of design diagram detailing. The collected data can be aggregated by country, region, national energy system or its subsystem. Figure 2 shows the aggregation (obtained in the DPGICS cartographic interface) of the power-plant installed capacities within the interconnected power systems (IPSs) of South Korea.

The levels of data aggregation can be different depending on the problem to be solved. The DPGICS automatically summarizes any object parameters for any year by the indicated key fields (by country ID, province, national power system, interstate power system, or by power plant type).

We formed a primary list of power plants in the OODB from the EniPedia.org open source. The power systems with their aggregated capacities (power plant types) shown in Figure 2, as well as individual power plants, are stored in the OODB like objects and their parameters.

The OODB object parameter values are also used as input data for the ORIRES optimization model being a

Table II optimal installed capacity (projected for 2035) by type of power plant (GW)

UPS	TPP			NPP	HPP	PSPP	WPP	SPP	TOTAL
	COAL	GAS	OIL						
Siberia (Russia)	25.09	3.58	0.00	2.40	28.62	0.00	0.00	0.00	59.69
East (Russia)	4.81	3.35	0.00	0.00	5.72	0.00	0.00	0.00	13.87
Sakhalin (Russia)	0.30	0.94	0.00	0.00	0.00	0.00	0.00	0.00	1.24
Mongolia	3.81	0.00	0.00		0.19	0.20	0.50	0.11	4.81
Northern China	489.00	20.30	0.00	24.10	3.20	25.00	35.00	24.00	620.60
North-East China	166.00	0.50	0.00	33.33	6.77	7.00	25.60	8.00	247.20
North Korea	3.00	7.00	2.00	0.00	7.01	0.00	0.57	0.71	20.29
South Korea	58.20	44.59	1.00	37.14	1.90	4.70	20.00	8.00	175.53
Japan	44.00	72.74	39.00	37.00	22.50	25.60	8.00	27.00	275.84

relevant functional part of DPGICS.

IV. Visualization of calculation results obtained with the model

The ORIRES mathematical model for optimization of power system expansion and operating conditions (hereinafter - the Model) is used to calculate various scenarios for creation of interstate power grids and optimal expansion of interconnected power systems. All the Model indicated parameters are customized through a DPGICS interface. The DPGICS uses the general algebraic modeling system (GAMS) [16], which starts with the DPGICS interface, reads the Model parameters set in the interface, and forms output tables with an optimal solution.

The DPGICS graphic block enables the selected options to be visually assessed and interpreted on maps, plots, as well as spreadsheets to be built. High-dimensional matrices of primary output data are converted into aggregated table templates with the results obtained by the Model. The aggregated tables with prepared results of forecasting the expansion of power systems in the countries of Northeast Asia for 2035 are demonstrated as an example. Table II presents the structure of optimal installed capacity (projected for 2035) for various types of power plants. In this Table, TPP means thermal power plant; NPP – nuclear power plant; HPP – hydro power plant; PSPP – pumped storage power plant; WPP – wind-power plant; SPP – solar power plant.

Indicators from Table II ("total" column) are demonstrated on the map through the cartographic user interface, Figure 3.

The indicators can be displayed as pie charts on the map, for any region in the world. This map is created automatically through the DPGICS cartographic interface. In addition, the constructed maps can be exported to the DPGICS web application.

The DPGICS considerably simplifies the creation of similar tables, reduces labor input when searching, checking, and forming the parameters for the optimization model, helps to visually represent the results of the obtained calculations in a graphic and cartographic form, and increase the research quality.

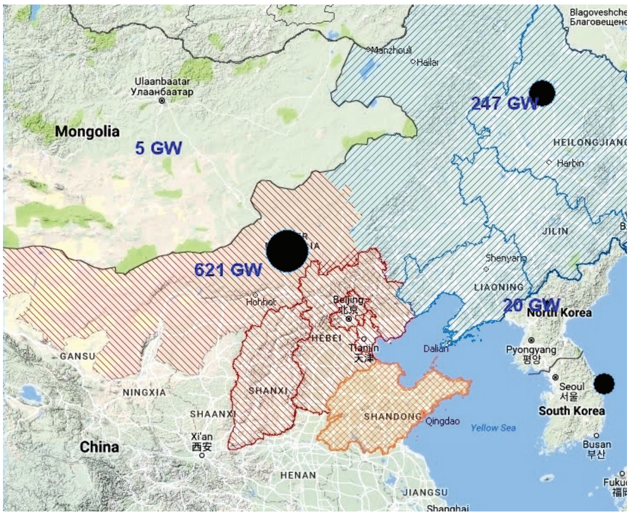

Fig. 3. Optimal installed capacities in EPSs of Northeast Asia countries.

V. Conclusion

We have developed and upgraded a geo-information computing system to support scientific research into the formation of interstate power grids. Apart from visualizing the power data, the DPGICS allows experts to perform optimization calculations and to forecast the IPG expansion by using the ORIRES mathematical optimization model.

We propose different algorithms for data collection/download into the object-oriented structure, and an original method of data storing and processing in the object-oriented database, visualizing the calculation results obtained using the ORIRES optimization model in the aggregated tables, on plots and maps.

The projects for power cooperation between Russia and Eurasian countries will enable us to practically test the developed algorithms and information technologies to forecast the expansion of national and interstate power grids. Our information technologies are universal, and can be applied to investigate interstate power grids in various regions of the world.

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Load-Reduction Capability Estimation for an Aggregator in Demand Bidding Program

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***Abstract* — In the recent decades, as a result of the increase in demand for electricity, it has been getting increasingly more frequent that the spinning reserve rate of the generators in Taiwan reaches lower level which reflects the emergency of power supply. The paper employs neural network (NN) to forecast the clearing price of the bidding through spinning reserve ratio and temperature data. Subsequently, the load-reduction of customers is forecasted through NN and fuzzy logic system. Fuzzy system is adopted for forecasting of low voltage LV customer to simulate the uncertainties of load reduction considering different situations during demand response (DR). In order to improve the forecasting accuracy when realistic data of DR is available, another procedure of correcting the customers' model for forecasting is proposed. Afterwards, the feasible contract capacity of load-reduction signed with Taiwan Power Company (TPC) is determined through an optimization algorithm. To actually assess the benefit, the real load data from Taiwan and Texas are used in the simulation.**

***Index Terms* — Demand response, demand-bidding, load-reduction forecasting.**

I. Introduction

In recent decades, the government has been promoting energy policies related to electric power, reflecting that the increase in demand for electricity has been an inevitable issue. In addition, along with the progress in living standards, the electricity demand grows up, which severely impacts the stability of electricity supply. The percent reserve margin of generators in Taiwan decreases year by year, which is also a symbol of the emergency of the power system. For the purpose of solving the crisis of energy shortage, initiative like promoting renewable energy resources such as photovoltaic power and wind power has arisen [1], and besides, smart grid [2] also emerges as a new paradigm in power grid. Combined with advanced communication technologies and control methodologies [3]-[5], smart grid has gradually become the mainstream trend of future electric industry owing to its ability of adjusting power generation, transmission, and distribution [6].

Among the features of smart grid, demand side management (DSM) is the modification of customer demand for energy through various methods such as adopting time of use tariff or even giving financial incentives [7]. Furthermore, there is another technique named automated demand response (ADR) cooperating with energy management system (EMS) which can automatically manipulate the appliances in houses or buildings through the advanced infrastructures installed for communication and control [8]. To sum up, both DSM and ADR are considerable approaches for peak shaving thus reducing the operating expense from expensive generators, and further deferring the capacity addition in the long run [9].

Subsequently, in order to encourage the involvement of more customers in the demand response (DR), a program called demand bidding is implemented in Taiwan. For the power utility, the main purpose of the program is to collaborate with the customers on DR, namely, each electricity customer can determine the available time of executing DR and bid the corresponding price, then the utility will judge whether the customer wins the bid or not. Similarly, the potential of participating in the demand-bidding program is worthy of assessment for the electricity customers.

As mentioned previously, the researches presented in [4], [5], [10]-[12] describe methods that improve the electricity consumption pattern for the industrial customer by means of adopting time-of-use (TOU) tariff. This way, the end-customers benefit from the kind of load management such as saving the electricity bills, and thereby the grid

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obtains a smoother load curve. Additionally, applications of energy management for the residential customers have been considered [13]-[15].

Home energy management methods proposed in [6] and [16] focus on DSM. Instead of using traditional DSM strategy, [6] presents a strategy based on load shifting technique for a large number of devices of several types. In [16], the authors demonstrate load shifting applied to seven different customer load sectors and illustrate the effects of the various DSM measures on the load shapes and on the system reliability indices used in generating capacity adequacy assessment.

In addition to DSM, DR is a further mechanism for reshaping the load profile [17], [18]. In a narrow sense, the DR here refers to the direct control of end-customers' loads at times of high wholesale market prices or when system reliability is jeopardized, then the incentive is paid to the customers for their cooperation. Moreover, home energy management system (HEMS) plays an important role that enables the residential customers to execute DR programs and load scheduling autonomously in the smart grid [9]. In [19], up to 20% reduction in daily electricity cost is achieved through its proposed HEMS management algorithm according to TOU.

Thereafter, the concept named virtual power plant (VPP) emerges as a combination of various small size distributed generating units which form a "single virtual generating unit" that can act as a conventional one and capable of being visible or manageable on an individual basis [20]. Furthermore, reference [21] takes DR into consideration by proposing a novel scheme of DR implementation, which is done based on the customers' submissions of candidate load profiles ranked in the preference order. The result of costs minimization for DR participants is verified as well, nevertheless, the uncertainties of the customers are not considered according to the presented scheme. Research like [22] discusses the bidding problem of DR in the day-ahead and real-time markets, yet the recent demand-bidding structure in Taiwan is different from other countries like the USA.

However, it is valuable to assess the profitable potential of participating in the demand-bidding program. As a result, owing to the lack of literature discussing the demand bidding problem in Taiwan, this paper attempts to propose a procedure evaluating the overall effect for an aggregator who takes part in the program.

II. Problem description and system modeling

A. Overall System Structure

In order to assess the potential of being an aggregator which contains lots of electricity customers for participating in the demand bidding program in Taiwan, this paper attempts to propose a method which helps the aggregator develop the optimal strategy that maximizes the electricity incentive received from the power utility for

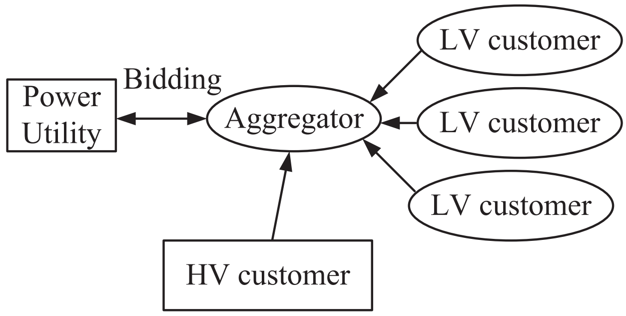


Fig. 1 Overall structure of the proposed Aggregator.

the bidding problem. Although LV customers cannot take part in DR in this stage, however, in this study, a future situation is mainly assumed that a HV customer serves as the aggregator who is able to cooperate with several LV customers on providing service like DR to the utility.

Fig. 1 illustrates the overall structure. In this structure, the smart meters, or advanced metering infrastructure

(AMI) known as the further form, are installed in each customer's house or building. By means of the smart meters, the electricity consumption can be monitored and be recorded along with time. The remote metering and the signal reception of electricity tariff or even DR can be implemented through the AMI as well. In the other words, it provides bidirectional communication between electricity customers and the power utility. In addition to AMI, another device called home energy management system (HEMS) which mainly comprises a gateway, controller for the appliances, and communication equipment, is necessary for a home to operate automated demand response (ADR) that involves automatic load shedding through program during DR events.

In the discussed structure, power consumption of equipment such as chiller can be adjusted by the energy management system for the HV customer during DR events. For the residential customer, air-conditioner and electric furnace are automatically controlled through HEMS during DR events. In addition, another function such as rescheduling the loads like clothes washer and clothes dryer is possible for the residential customers as well.

Finally, once the demand response is finished successfully, each customer and the aggregator are able to receive the corresponding incentive. In the proposed structure, it is reasonable for the aggregator to take commissions from the LV customers who take part in the DR program through the aggregator or even share the HEMS costs with the aggregator. To sum up, the aggregator can profit not only from the incentives of DR but also from the commissions taken from LV customers. On the other hand, the LV customers' profits consist of incentives of DR and the cost savings through load scheduling.

B. Demand bidding of Taiwan Power Company

It is undeniable that the spinning reserve rate, which represents the situation of electricity supply, has been lower and lower since 2012, especially on May 31, 2016, which has the lowest spinning reserve rate ever, about 1.64%. In order to improve the situation, a considerable way is to reduce the emergency of electricity supply from demand side, that is, to strengthen the DSM, and DR is one of the widely known terms. Furthermore, DR is completed by directly reducing the demand of the power customers during the peak period, and corresponding reward would be paid to the cooperative customers, thus for the utility, it is an issue to strike a balance between the cost of power generation and the payment for DR. As a result, the demand-bidding mechanism is utilized in Taiwan, which allows a lot of customers to decide their acceptable time to reduce their power consumption and bid a price for the reduction capacity to Taiwan Power Company (TPC), then TPC would determine which customers win the bid according to their concern of cost or others.

The business model of DR is a bidding process in Taiwan [23], [24], including the economical type, reliable type, and aggregated type. The general rule to evaluate a DR event is as follows:

1. Customer can decide the month of DR execution and the monthly minimum contract capacity of load-reduction.
2. Customer can decide the DR execution duration, which can last either 2 hours or 4 hours each day, and it cannot exceed 36 hours in total for the same month.
3. The bidding price per kWh cannot exceed 10 NT$/kWh.
4. The customer baseline load (CBL) is determined by the average value of the same period of DR execution time in previous five days except for load-reduction day, off-peak day, and weekends.
5. The actual reduction amount is determined by the difference between CBL and the maximum demand during the DR execution time. The amount is treated as 0 if it is less than the minimum contract capacity of load reduction.

More specifically, Fig. 2 presents an explanation.

III. Problem Formulation and the Proposed Bidding Strategy Optimization

In the proposed procedure, the forecasting of possible winning price for the demand-bidding program is firstly addressed, the load reduction for each role is then estimated through the designed models, and the last part deals with the bidding decision determining the capacity of load reduction. The entire flowchart is shown in Fig. 3.

A. Forecasting Models

The forecasting process in the proposed structure is executed for the demand-biddings of the forthcoming month, i.e. a month-ahead forecasting is designed, and besides, the decisions for the month are determined after each complete execution of the forecasting process. Additionally, the required inputs for the overall forecasting are mainly the spinning reserve rate and temperature data, which are predicted monthly and available from the official website of TPC and Central Weather Bureau (CWB) in Taiwan, and each residential customer's will for load reduction during DR.

1) Forecasting of Clearing Price for Demand-Bidding

In order to decide the bidding price, which is most probably winning for each DR event, a simple forecasting model of feed-forward artificial neural network (FNN) is proposed. The employed FNN uses the back-propagation algorithm to reach a better forecasting outcome [25].

For the mentioned neural network, its data inputs are designed as the forecasted temperature and the forecasted

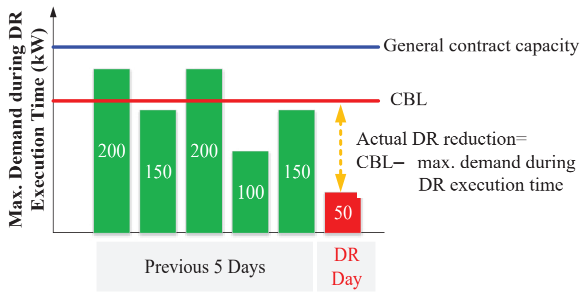


Fig. 2. Example for the calculation of actual load reduction.

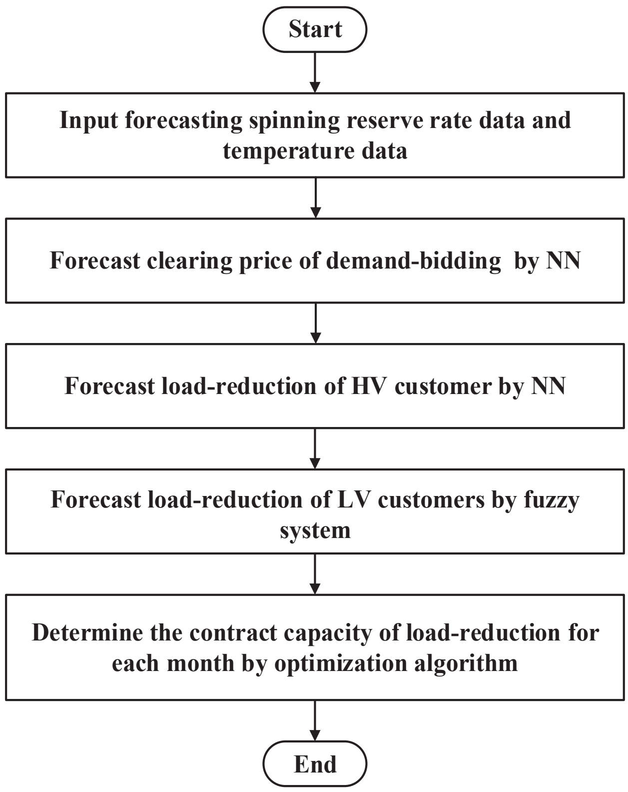


Fig. 3. Flowchart of proposed method.

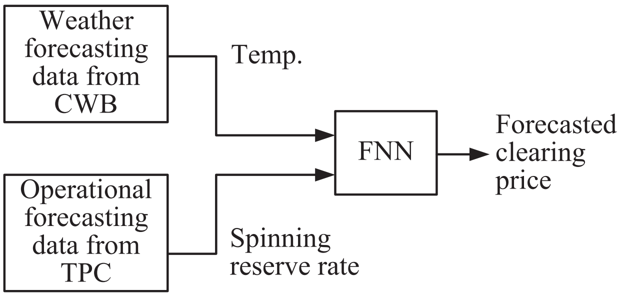


Fig. 4. Structure of the FNN for clearing price forecasting.

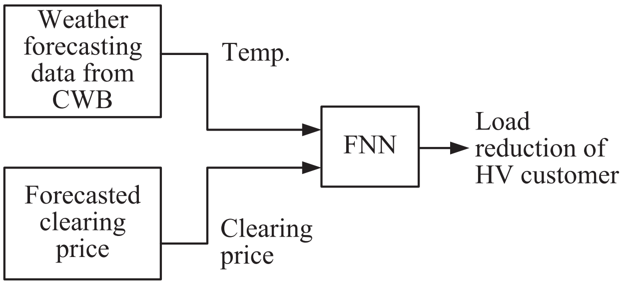


Fig. 5. Structure of the FNN for the forecasting of HV customer.

spinning reserve rate, which are available from the websites of CWB and TPC respectively, in the end, the data output of the neural network is the forecasting bidding price for the aggregator. The structure of the FNN used for the bidding price forecasting is shown in Fig. 4.

On the other hand, when it comes to the FNN training procedure, the historical data of the temperature and the spinning reserve rate corresponding to the past DR events are chosen as the training data. In spite of the fact that the historical data are similarly possible to be obtained from the websites of CWB and TPC, the historical data of the clearing prices for DR is another difficulty for the training procedure. In this case, the training output is replaced by the marginal cost of generation, which is estimated by the situation of generation for different generation units, since the marginal cost of generation is positively relevant to the clearing price.

2) Forecasting of Load Reduction for the High-Voltage Customers

For the aggregator who is going to participate in the demand-bidding mechanism, the estimation of the load-reduction amount for the forthcoming event is another important issue. Additionally, since the pattern of consuming electricity for HV customers, such as the industrial customers, is much more regular than the LV or residential customers, the load-reduction amount of the HV customer is forecasted by applying FNN, too.

Being similar to the forecasting of bidding price, the FNN is employed for the forecasting of the load reduction for the HV customer as well. The bidding price and the temperature, which are the two factors that influence the load reduction most likely, are adopted as the data inputs for this forecasting model, and the load-reduction amount is predicted. Fig. 5 depicts the forecasting model of the load-reduction estimation for the HV customer in the paper. Note that the input of bidding price is the clearing price produced from the previous forecasting FNN in the practical application. Besides, the training procedure can be accomplished by using historical data of temperature, the clearing price of the past demand-bidding events and the customer's load profile at the corresponding time.

3) Forecasting of Load Reduction for the Low-Voltage Customers

Being distinct from the HV customer, the pattern of power consumption for LV customers, which are residential customers here, is hardly to be predicted because each customer may have different habits or preferences for electricity consumption. For the sake of forecasting the load reduction for the LV customers considering the mentioned uncertainties, a fuzzy logic system is used here.

Three factors are selected as the inputs of the fuzzy logic system, the actual bidding price of the aggregator, customer's preference for the execution time of DR, and customer's preference for incentive, the output of fuzzy logic is the estimated percentage of load reduction for the appliances.

Regarding each factor, the bidding price decided by the aggregator impacts the final incentive for each customer, and the preference settings reflect the situation whether the load reduction is available or acceptable during the DR for each customer. The bidding price is normalized to represent its level, thus the three input factors' values of the fuzzy

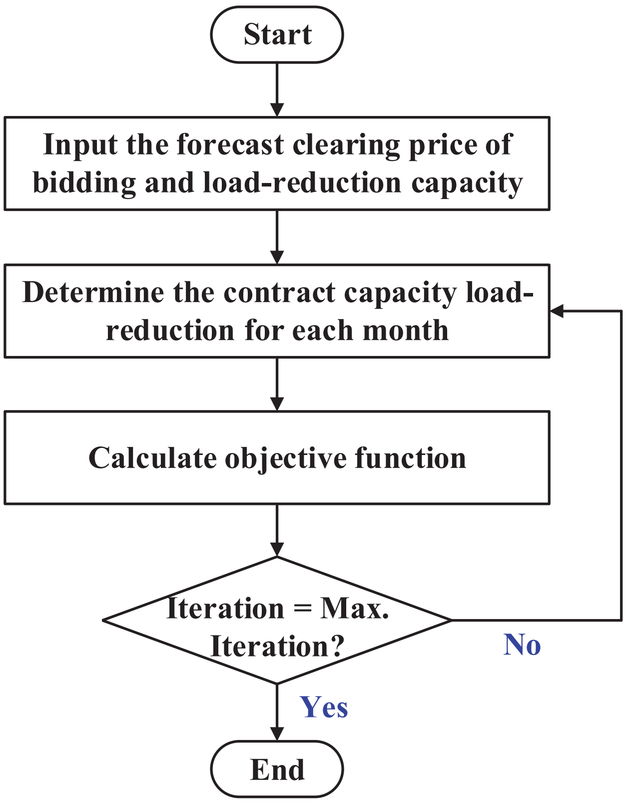


Fig. 6. Flowchart of proposed bidding strategy selection method.

system are all ranged from 0 to 1. For each of the three factors, a higher value would lead to a larger percentage of load reduction, which also means the customer is willing to reduce their electricity consumption under the situation.

Last but not least, the uncertainty of the power usage in the residential customers is an inevitable issue when forecasting the load-reduction amount. Therefore, for every residential customer, the uncertain characteristic is simulated by using random numbers that are generated according to the normal distribution as the inputs of the preference setting for the fuzzy logic system.

Moreover, considering the practicality, the preferences of every residential customer can be known through questionnaire surveys, then it would be possible to build up the normal distribution curve for each customer.

B. Formulation of Bidding Strategy Optimization

In the paper, the main purpose is to simulate an aggregator that takes part in the demand-bidding mechanism, maximizing the profit and finally evaluating the entire benefit for the discussed structure. As a result, in addition to the estimation of possible load reduction for the forthcoming DR, it is necessary to determine the contract capacity of minimal load reduction. Consequently, an optimization method is employed to maximize the profit based on the forecasting, the whole process is demonstrated in Fig. 6.

In the proposed structure, two types of the demand-bidding programs are discussed, i.e. reliable demand bidding and aggregated demand bidding. They can be described as follows:

1) Reliable Demand Bidding

According to the rule of the reliable DR, the overall objective function, which is to maximize the total incentive obtained from TPC is shown in (1). Equation (2)-(6) state the variables composing (1).

$$\max \sum_{m=1}^{12} IDC_m + \sum_{m=1}^{12}\sum_{d=1}^{n}(IEC_{m,d} + Pen_{m,d}) \tag{1}$$

$$IDC_m = p_{\text{contr},m} \times [P_{\text{IDC}} \times \frac{\sum_{d=1}^{n} b_{\text{s},m,d}}{n}(1-b_{\text{as},m}) + P_{\text{IDC,as}} \times b_{\text{as},m}] \tag{2}$$

$$IEC_{m,d} = P_{\text{bid},m,d} \times p_{\text{FLR},m,d} \times b_{\text{s},m,d} \tag{3}$$

$$Pen_{m,d} = 0.5 \times P_{\text{bid},m,d} \times (p_{\text{FLR},m,d} - p_{\text{contr},m}) \times (1 - b_{\text{s},m,d}) \tag{4}$$

$$\begin{cases} b_{\text{s},m,d} = 1 & \text{if } p_{\text{FLR},m,d} - p_{\text{contr},m} \geq 0 \\ b_{\text{s},m,d} = 0 & \text{if } p_{\text{FLR},m,d} - p_{\text{contr},m} < 0 \end{cases} \tag{5}$$

$$\begin{cases} b_{\text{as},m} = 1 & \text{if } \sum_{d=1}^{n} b_{\text{s},m,d} = n \\ b_{\text{as},m} = 0 & \text{if } \sum_{d=1}^{n} b_{\text{s},m,d} < n \end{cases} \tag{6}$$

Where

- IDC_m is the incentive of demand charge for the month m (NTD).
- $IEC_{m,d}$ is the incentive of energy charge for the day d in the month m (NTD).
- $Pen_{m,d}$ is the penalty for the day d in month m (NTD).
- $P\text{contr}_{,m}$ is the contract capacity of load reduction for the month m (kW).
- P_{IDC} is the incentive price for the demand charge, which equals 60 NTD/kW.
- P_{IDC},as is the incentive price for the demand charge particularly when all the DRs are executed successfully in the month m, which equals 72 (NTD/kW).
- $P_{\text{bid},m,d}$ is the forecasting clearing price for the day d in the month m.
- $P_{\text{FLR},m,d}$ is the total forecasting load-reduction capacity for the day d in the month m.
- $b_{\text{s},m,d}$ is the binary number of execution result, i.e. whether the DR on the day d in the month m succeeded or not.
- $b_{\text{as},m,d}$ is the binary number of monthly execution result, i.e. whether the DRs in the month m all succeeded or not.

$$0 < P_{\text{bid},m,d} \leq 10 \tag{7}$$

$$p_{\text{contr},m} \geq 50\ \text{kW} \tag{8}$$

The inequality constraints are listed in (7) and (8). Inequality (7) represents the allowable price of demand bidding. Inequality (8) describes the monthly minimal load reduction that should be signed with TPC, then there would be a penalty if there is any DR event with load reduction below $p_{\text{contr},m.}$

2) Aggregated Demand Bidding

According to the rule of the aggregated DR, the overall objective function is presented in (9). Equation (10), (11) state the variables composing (9)

$$\max \sum_{m=1}^{12}\sum_{d=1}^{n} IEC_{m,d} \tag{9}$$

$$IEC_{m,d} = P_{\text{bid},m,d}[1.05 p_{\text{FLR},m,d} \times b_{\text{er},md} + p_{\text{FLR},m,d} \times (1 - b_{\text{er},m,d})] \tag{10}$$

$$\begin{cases} b_{\text{er},m,d} = 1 & \text{if } 0.6 \leq \dfrac{p_{\text{FLR},m,d}}{p_{\text{contr},m}} \leq 1.5 \\ b_{\text{er},m,d} = 0 & \text{if } \dfrac{p_{\text{FLR},m,d}}{p_{\text{contr},m}} < 0.6 \text{ or } \dfrac{p_{\text{FLR},m,d}}{p_{\text{contr},m}} > 1.5 \end{cases} \tag{11}$$

Where

- $\boldsymbol{IEC}_{m,d}$ is the incentive of energy charge for the day *d* in the month m (NTD).
- $\boldsymbol{P}_{\text{bid},m,d}$ is the forecasting clearing price for the day *d* in the month *m*.
- $\boldsymbol{p}_{\text{FLR},m,d}$ is the total forecasting load-reduction capacity for the day *d* in the month *m*.
- $\boldsymbol{b}_{\text{er},m,d}$ is the binary number of DR execution rate, i.e. the ratio of reduction capacity to the contract load-reduction capacity.

The inequality constraints are listed in (12) to state the monthly minimum load reduction required for each DR in month m.

$$p_{\text{contr,m}} \geq 100 \text{ kW} \tag{12}$$

It is used as a standard to evaluate the load-reduction capacity, if the amount is close to the contract capacity, then additional 5% of the bidding price would be paid as a reward. Note that the lower limit of the contract capacity for aggregated demand bidding is higher than that for reliable demand bidding. Besides, the limit of bidding price is the same as that of reliable demand bidding.

C. Cost Saving of Load Scheduling

The LV customers can save their electricity costs by rescheduling the schedulable loads in their buildings through HEMS according to different electricity tariffs.

Where

- $p_{s,d,h}$ is the total power consumption of schedulable loads at hour h on the day d (kWh).
- $p'_{s,d,h}$ is the total power consumption of schedulable loads after load scheduling at hour h on the day d (kWh).
- $P_{d,h}$ is the hourly electricity price at hour h on the day d (NTD/kWh).

D. Formulation Correction for Low-Voltage Customer

Considering the fact that there may be forecasting error when estimating the load reduction of LV customers, a correction method is proposed to improve the practicality of the model as long as the actual data of the load reduction for each customers is available in the future. The flowchart of the correction method is shown in Fig. 7.

In this part, the goal is to correct the preference settings through the historical data of DR. Specifically, by comparing the historical data with the results forecasted by the built fuzzy system and current preference settings, and tuning the preference settings to make the forecasting result of load reduction as close as possible to the historical one. That is to say, the objective is to minimize the mean absolute percentage error (MAPE) between the adjusted preference settings and the historical data, as shown in (13).

$$\min \frac{1}{n}\sum_{i=1}^{n}\left|\frac{LR_{\text{f},i}-LR_{\text{a},i}}{LR_{\text{a},i}}\right| \tag{13}$$

Firstly, in (13), $LR_{f,i}$ and $LR_{a,i}$ are the forecasted and actual load reduction respectively for each DR event. Secondly, the constraints are listed in (14) and (15).

$$0 \leq pref_{\text{inc},i} \leq 1 \tag{14}$$

$$0 \leq pref_{\text{time},i} \leq 1 \tag{15}$$

In these constraints, $pref_{inc,i}$ and $pref_{time,i}$ are the customer preferences for incentive and for execution time of the ith DR event, which are used as the inputs of the fuzzy logic system, and thus directly influence the prediction of load reduction. Note that the two preference indices are the decision variables in the optimization.

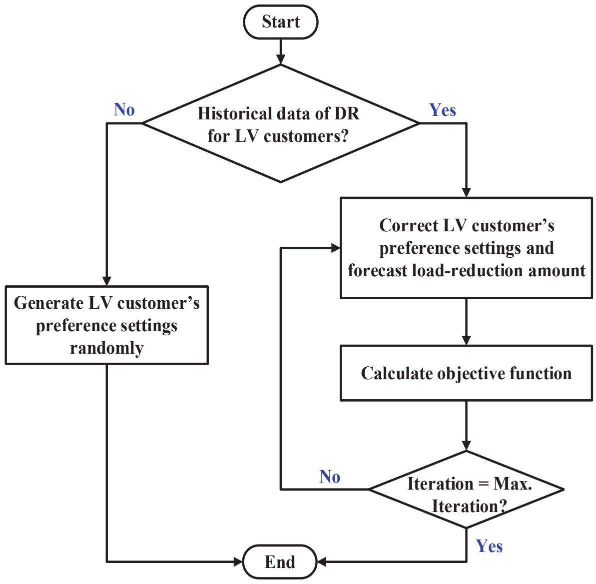


Fig. 7. Flowchart of proposed preference settings correction method.

IV. Simulation Results

A. Simulation Parameters

1) Load Profiles of the Customers

In this section, the daily load data of summer and winter are employed for demonstration. There are two types of customers, HV and LV customers, and their load patterns are discussed in the following part. Note that it is assumed in this paper that one HV customer serving as aggregator and one thousand LV customers join in the DR program.

- High-Voltage Customer

As mentioned previously, in this paper, the aggregator is composed of one HV customer and lots of LV residential customers. For the HV customer, its loads can be simply divided into controllable loads and non-controllable loads here. The daily load patterns of January and August are used to stand for winter and summer, as shown in Fig. 8 and Fig. 9.

The load profile is the actual electricity use data

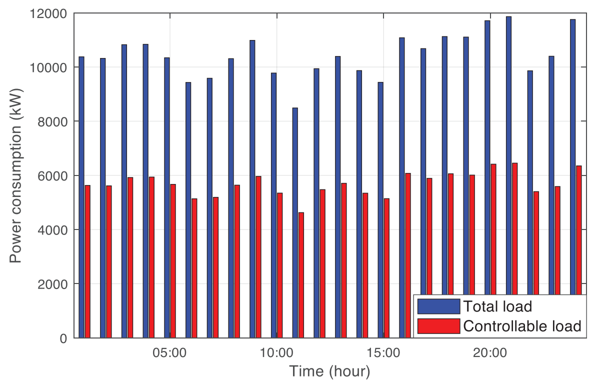


Fig. 8 Daily load profile of high-voltage customer (Jan. 2016).

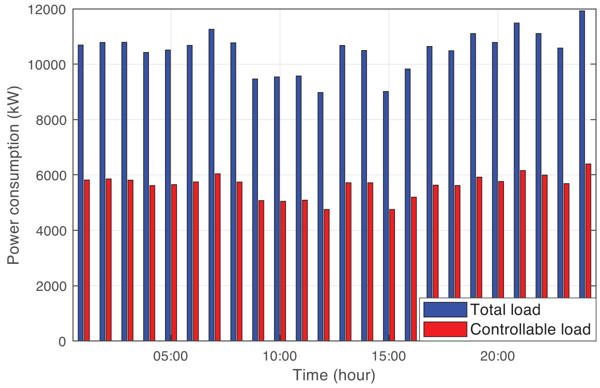


Fig. 9. Daily load profile of high-voltage customer (Aug. 2016).

measured from an industrial customer in Taiwan in 2016. Note that because of lack of actual controllable load data, the maximum of controllable loads, which are chillers here, is approximately assumed as half of the total load for load-reduction. Additionally, January and August of 2016 are chosen as winter and summer for the simulation, which will be scaled up to one year.

- Low-Voltage Customer

Subsequently, for the LV customers, which are the residential customers, two types of houses would be discussed in the paper, one is the apartment and the other is the single-house. The realistic data of about 260 LV customers comes from Austin, Texas [28]. In the simulation, the number of LV customers is scaled up to 1000.

Different from the HV customer, the house loads are further classified into controllable loads and schedulable loads, the former includes air-conditioner and electric furnace, and the latter includes dishwasher, clothes washer, clothes dryer, and electrical vehicle charger. For the same reason as the HV customer, Fig. 10 and Fig. 11 individually depict the daily load profiles of the apartment customers for summer and winter. Similarly, Fig. 12 and Fig. 13 illustrate the load profiles of the single-house customers.

2) Electricity Tariffs

To verify the effect of different tariffs on the cost saving for LV customers, two tariffs are used as example for a brief comparison. The first tariff is the 2-stage time of use tariff from TPC [26], and the second tariff [27] is actually the local marginal price of the day-ahead market from Electricity Reliability Council of Texas (ERCOT). The price is related to the situation of supply and demand, which reflects congestion.

Table 1. Simulation scenarios.

	HV customer	LV customers	
	DR type	DR type	Customer type
Scenario 1	Reliable	Aggregated	Apartment
Scenario 2	Reliable	Aggregated	Apartment
Scenario 3	Aggregated	Aggregated	Single-house
Scenario 4	Aggregated	Aggregated	Single-house

B. Forecasting of Load Reduction and Incentive

Firstly, the necessary term that must be assessed is the bidding price, thus the prediction result of the clearing price of demand bidding is simply demonstrated. Subsequently, there are four scenarios simulated in this section, as listed in Table 1 and the forecasting results are shown in the following section.

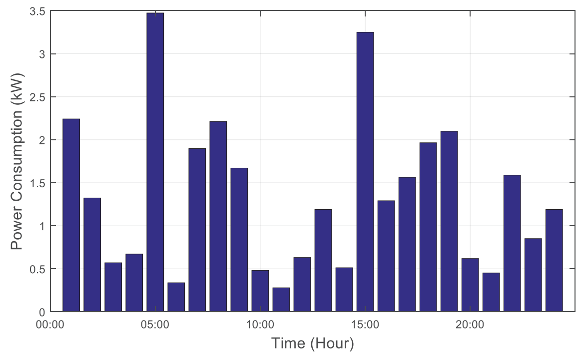
1) Forecasting Result of Clearing Price

The bidding prices are predicted through NN described previously, the inputs and output are presented in Fig. 14. Note that the forecasted bidding prices are regarded as the clearing prices, which means the maximum price accepted by TPC. There are 7 times and 8 times of DR, which lasts 4 hours each time, in January and August, respectively.

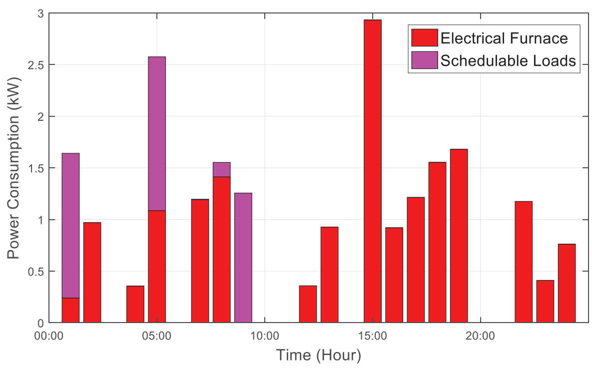
2) Forecasting Results of Scenario 1

For HV customer, the forecasting results of load-reduction and corresponding incentive are depicted in Fig. 15 - Fig. 17. In the presented results, the historical data of load reduction are used as actual load reductions, and the forecasting results come from the forecasting model. Note that the HV customer participates in reliable DR, thus it is reasonable for the penalty if the contract capacity of load reduction is not satisfied.

For LV customers, the forecasting results of load-reduction and corresponding incentive are illustrated in Fig. 18 and Fig. 19. However, due to lack of the historical data, only the forecasting results are presented in this stage.

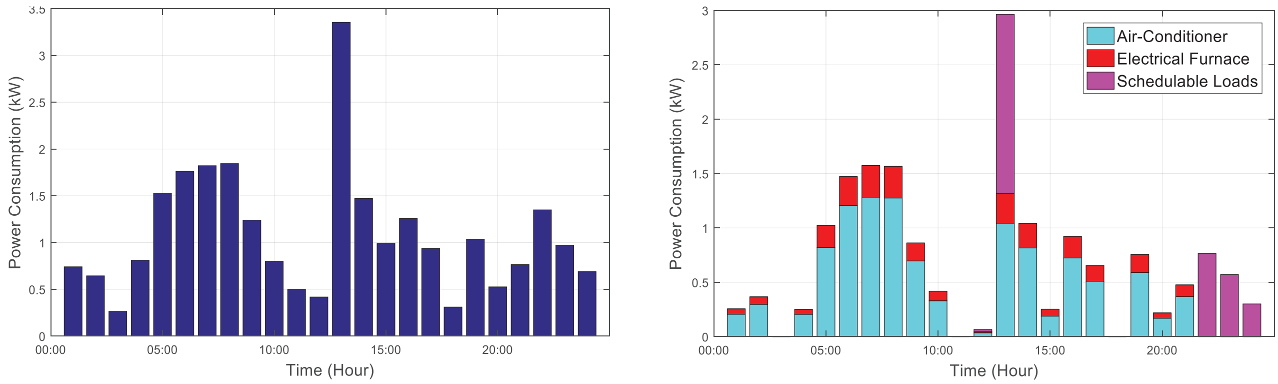


(a)



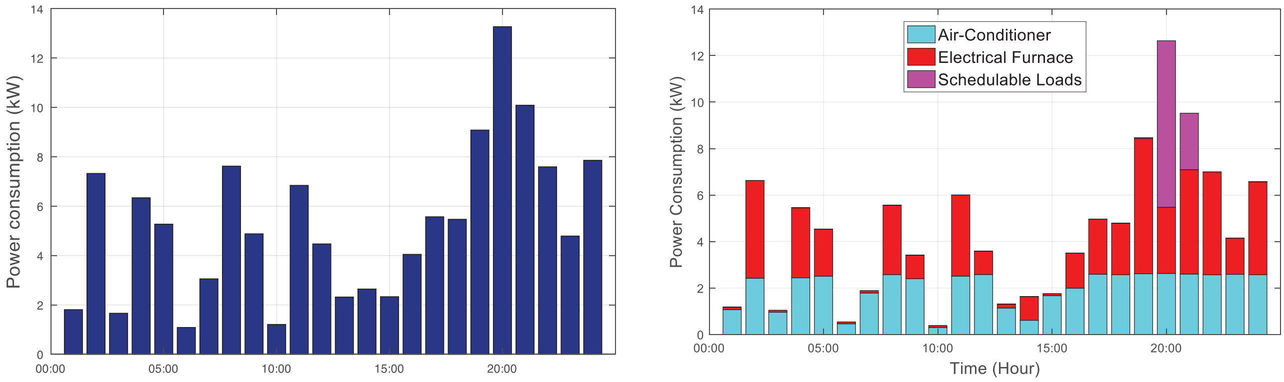
(b)

Fig. 10. Daily load profile of apartment customer (Jan. 2016) (a) Total load, (b) Schedulable loads.



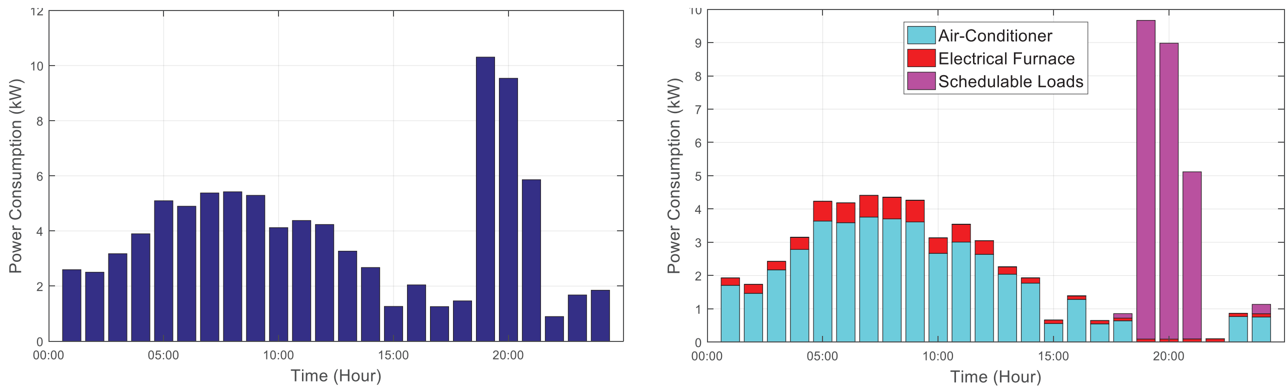
(a) *(b)*

Fig. 11. Daily load profile of apartment customer (Aug. 2016) (a) Total load, (b) Schedulable loads.



(a) *(b)*

Fig. 12. Daily load profile of single-house customer (Jan. 2016) (a) Total load, (b) Schedulable loads.



(a) *(b)*

Fig. 13. Discussed tariffs in the paper (a) 2-stage TOU tariff of TPC, (b) Real time price of ERCOT.

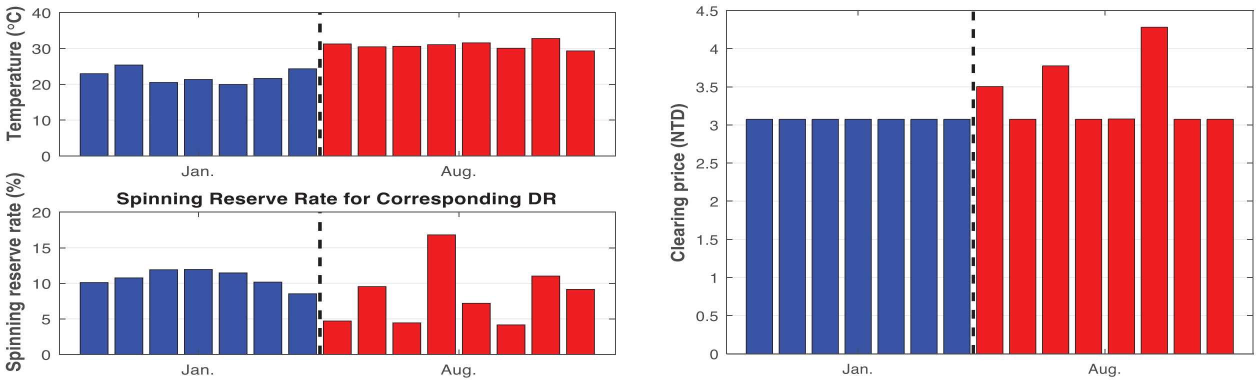
Note that the LV customers take part in the aggregated DR, hence the contract capacities of load reduction determined by the DR algorithm are feasible according to the demand bidding rule introduced previously.

In forecasting results, the dash lines represent the optimal contract capacities of load reductions determined by DR algorithm. For example, the blue dash lines in Fig. 15 and Fig. 16 are the optimal contract capacities of Load reduction for the actual load reductions; the red dash lines are the same but for the forecasted load reductions. If the red dash line is close to the blue dash line, then it means that the result of load reduction forecasting is close to actual one.

3) Forecasting Results of Scenario 2

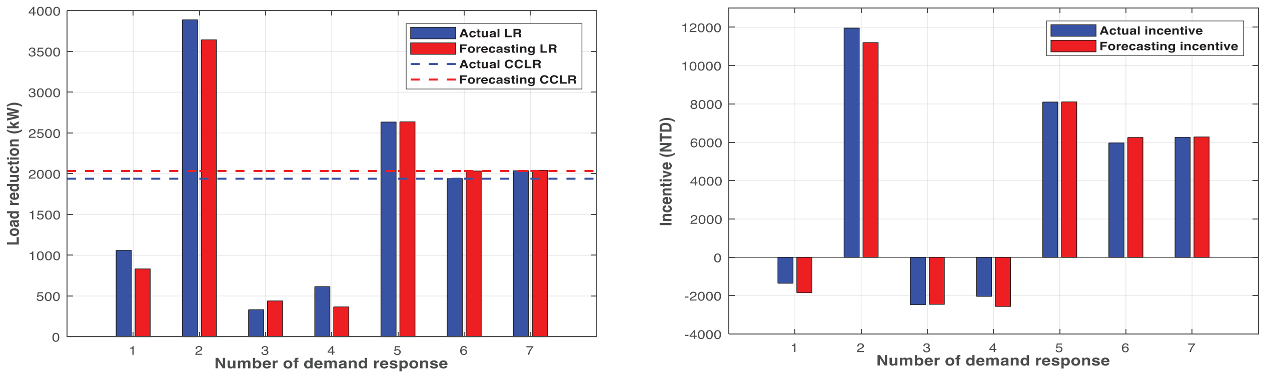
Similar to scenario 1, the main difference between scenario 1 and scenario 2 is the type of LV customers. Therefore, the forecasting for HV customer is totally the same as presented in scenario 1. The forecasting result of load reduction and incentive for the single-house customers are shown in Fig. 20 and Fig. 21.

According to the results, the overall incentives received by single-house customers apparently surpass those of apartment customers. The results are directly led by the total capacity of the controllable loads. However, the capacity of schedulable loads is another significant source



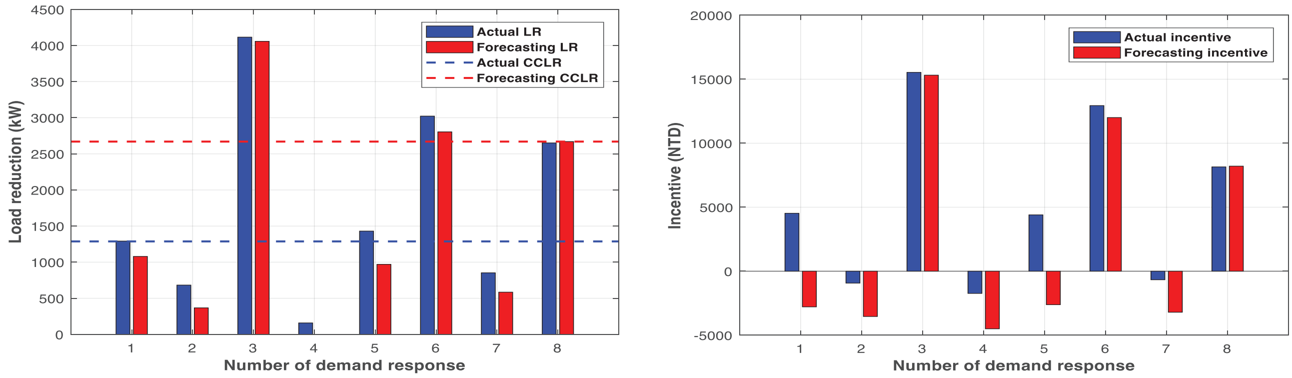
(a) (b)

Fig. 14. Forecasting result of bidding price (a) Inputs of the neural network, (b) Output of the neural network.



(a) (b)

Fig. 15. Forecasting result of HV customer in scenario 1 (winter) (a) Load reductions (LR) and contract capacity of load reduction (CCLR), (b) Incentives of energy charge for the corresponding load reduction.



(a) (b)

Fig. 16. Forecasting result of HV customer in scenario 1 (summer) (a) Load reductions (LR) and contract capacity of load reduction (CCLR), (b) Incentives of energy charge for the corresponding load-reduction.

that indirectly influences the load reduction during DR. Based on the calculation rule for actual load reduction, the load reduction for each DR can be raised up through technical manipulations of the schedulable loads. In other words, the schedulable loads are shifted to the same hours of DR execution during five days before DR event to heighten the baseline load, thus increasing the actual load reduction.

4) Forecasting Results of Scenario 3

Different from the previous scenarios, the HV and LV customers join the aggregated DR together. As a result, the historical load reduction data of the HV customer are used as the basis for the comparison of forecasting. Even though there are only the forecasting results for LV customers, the simulation results show the aggregated load-reduction capacity of HV and LV customers, as presented in Fig. 22 and Fig. 23.

Since it is much more stable for the HV customer to reduce electricity consumption during DR event than for the LV customers, there is no doubt that the success rate for execution DR would be higher through the aggregation of HV and LV customers. However, due to the absence of the incentive for demand charge in the aggregated DR, the overall incentive for the HV customer is accordingly less than that received in scenario 1 and scenario 2. Moreover, since there is no penalty in the aggregated DR, it is suitable for the HV customer even if the forecasting accuracy is not precise enough.

5) Forecasting Results of Scenario 4

As the comparison of scenario 1 and scenario 2, the simulation results here show the difference from scenario

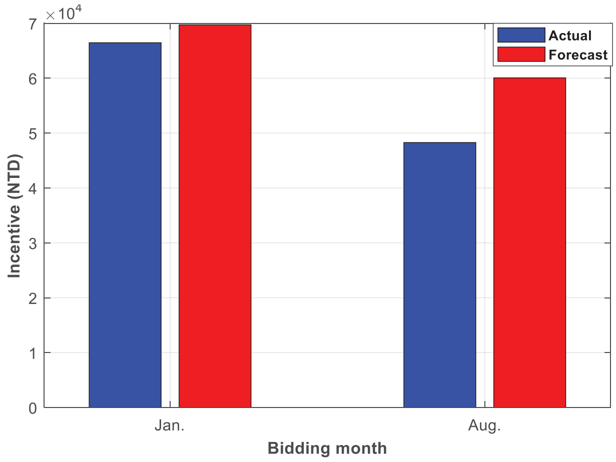


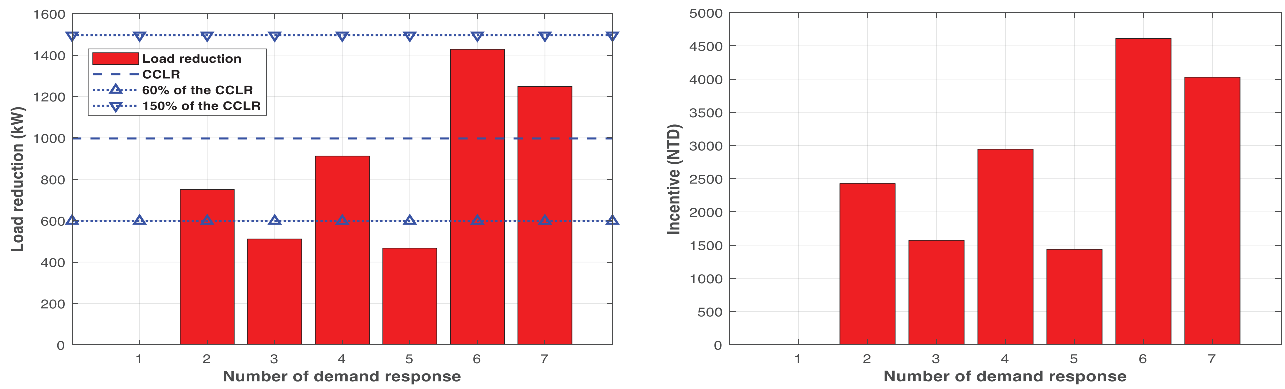
Fig. 17. Incentive of demand charge of HV customer.

3. In scenario 4, the HV customer cooperates with single-house customers on the aggregated DR as shown in Fig. 24 and Fig. 25. As discussed previously, with the larger controllable load capacity, the single-house customers have the potential to earn more incentive for DR execution. Besides, the HV customer chooses to take part in aggregated DR, which is a more conservative option.

In summary, by means of appropriately selecting the LV customers who have more potential in DR, the overall incentive received from TPC would be considerable even if the HV customer participates in the aggregated DR. In order to make a clearer comparison, the total incentives for the four scenarios are listed and discussed in the following section.

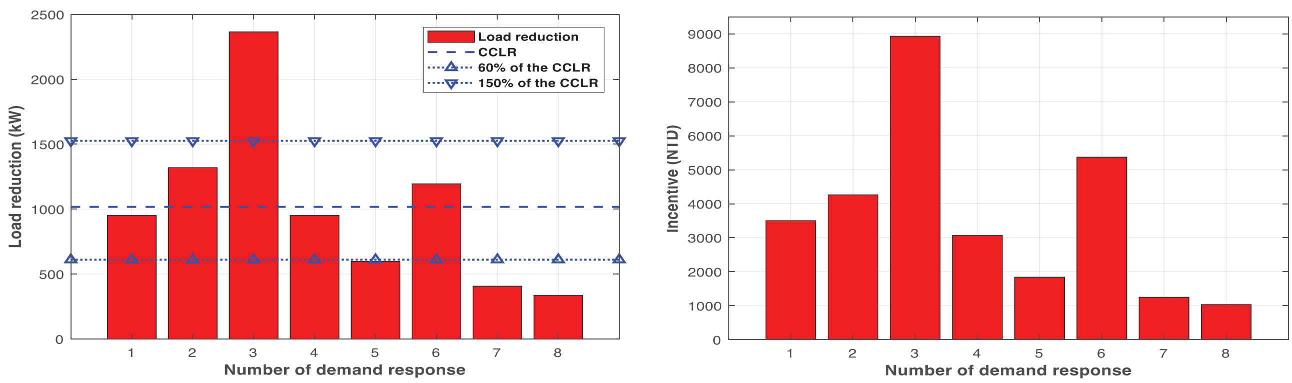
6) Summary for the simulation of the four scenarios

To sum up the four scenarios, Fig. 26 shows the effective annual incentive received. As the comparison in the Figure, it is obvious that the total incentive of scenario 2, where the HV customer participates in reliable DR and cooperates with the single-house customer, is the highest due to the additional incentives of demand charge for reliable DR and the incentives of energy charge earned through the large controllable load capacity of the single-house customers. Nevertheless, there is still an issue that is the risk for selecting reliable or aggregated DR, which is discussed in the later section.



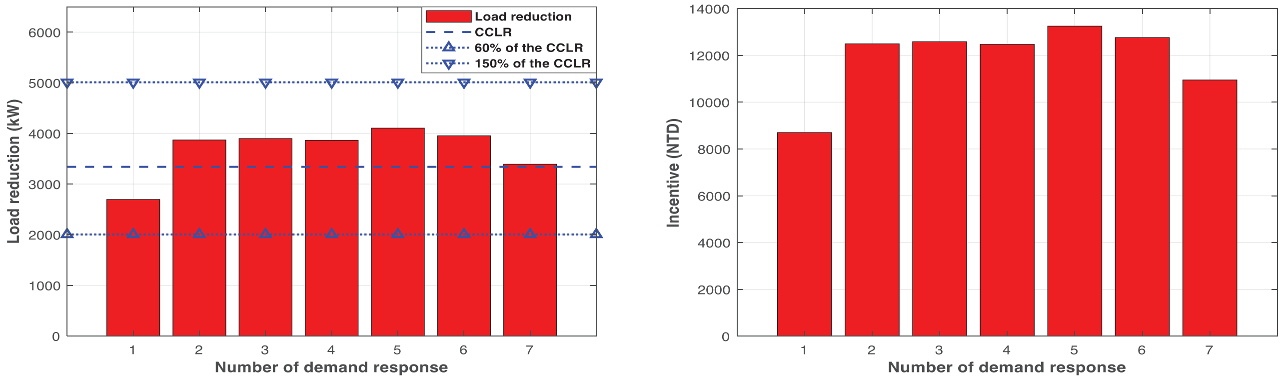
(a) ***(b)***

Fig. 18. Forecasting result of LV customer in scenario 1 (winter) (a) Load reductions (LR) and contract capacity of load reduction (CCLR), (b) Incentives of energy charge for the corresponding load reduction.



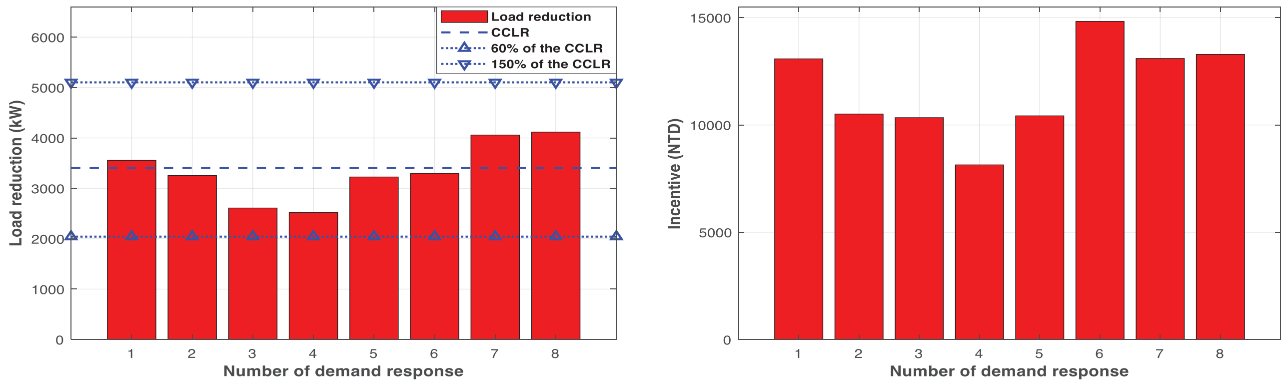
(a) ***(b)***

Fig. 19. Forecasting result of HV customer in scenario 1 (summer) (a) Load reductions (LR) and contract capacity of load reduction (CCLR), (b) Incentives of energy charge for the corresponding load reduction.



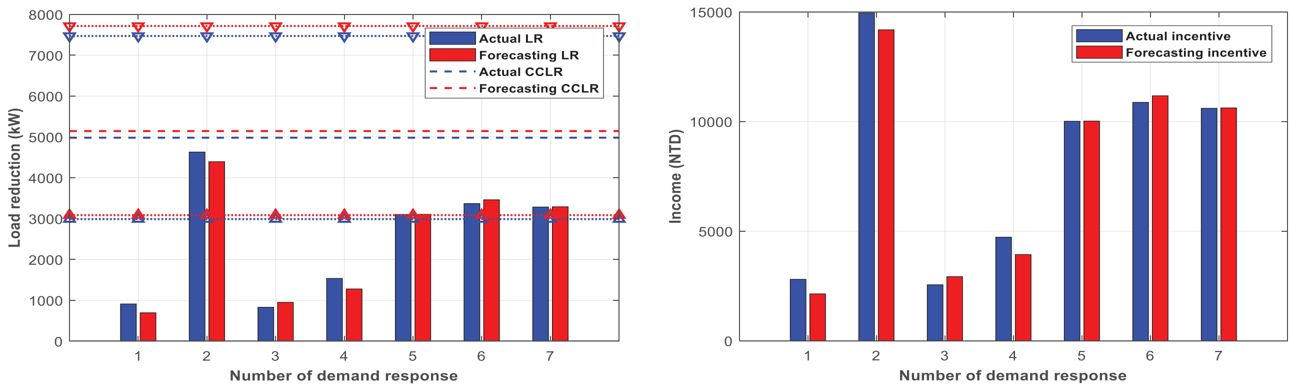
(a) *(b)*

Fig. 20. Forecasting result of LV customer in scenario 2 (winter) (a) Load reductions (LR) and contract capacity of load reduction (CCLR), (b) Incentives of energy charge for the corresponding load reduction.



(a) *(b)*

Fig. 21. Forecasting result of LV customer in scenario 1 (winter) (a) Load-reductions (LR) and contract capacity of load-reduction (CCLR), (b) Incentives of energy charge for the corresponding load-reduction.



(a) *(b)*

Fig. 22. Forecasting result of HV and LV customers in scenario 3 (winter) (a) Load reductions (LR) and contract capacity of load reduction (CCLR), (b) Incentives of energy charge for the corresponding load reduction.

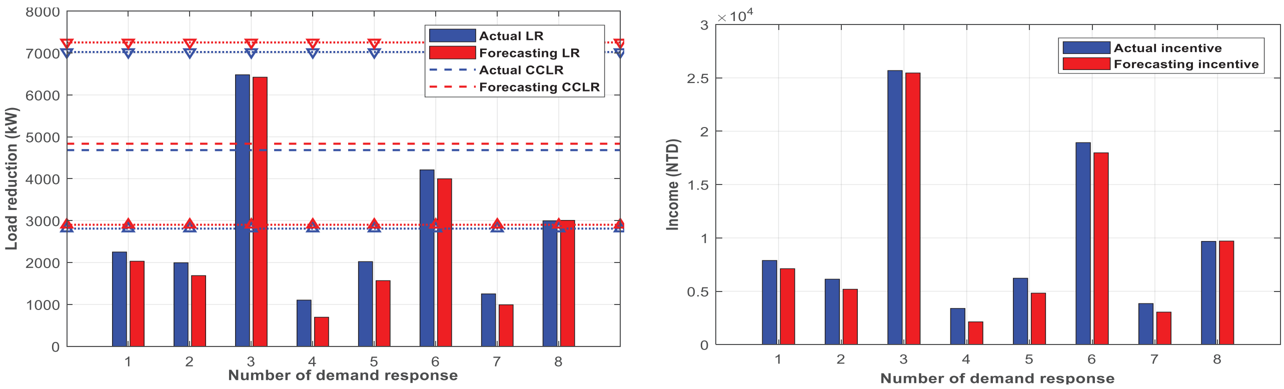
C. Cost Savings of Load Scheduling Considering Different Tariffs

For each LV customer who has established HEMS in house, the profit can be obtained not only from the DR program but also from the cost saving from daily power consumption. Therefore, a simple comparison of the cost saving by load scheduling for different kinds of customer is performed. In the meanwhile, two tariffs are compared for the reason that more and more tariffs may be published in the future.

It is apparent that the single-house customers have much greater saving than the apartment customers owing to the significant difference in their power consumption of schedulable loads. Besides, another noticeable point is that the effect of different tariffs, the real-time price of ERCOT brings the LV customers additional savings due to the larger price difference between hours in one day.

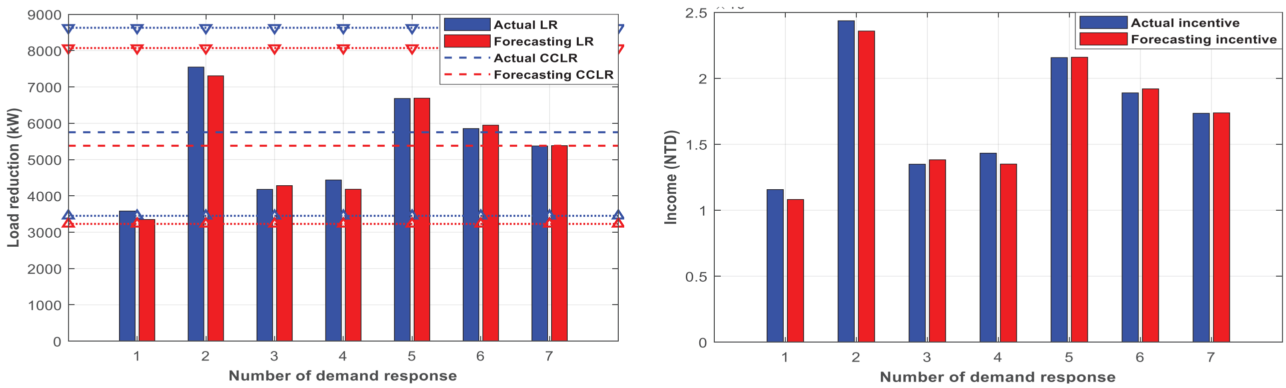
1) Cost-Benefit Analysis

In order to evaluate the profit, the hardware cost is taken into account. The recent costs of HEMS are approximately



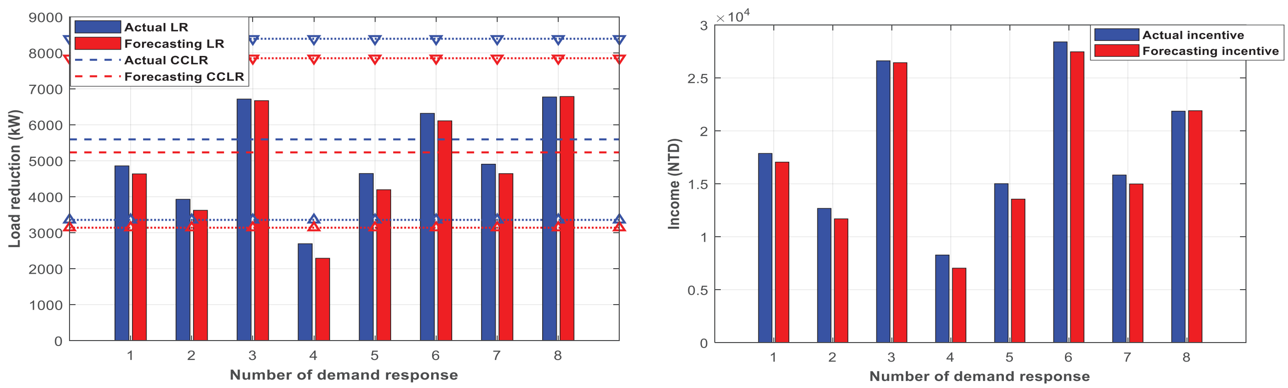
(a) *(b)*

Fig. 23. Forecasting result of HV and LV customers in scenario 3 (summer) (a) Load reductions (LR) and contract capacity of load reduction (CCLR), (b) Incentives of energy charge for the corresponding load reduction.



(a) *(b)*

Fig. 24. Forecasting result of HV and LV customers in scenario 4 (winter) (a) Load reductions (LR) and contract capacity of load reduction (CCLR), (b) Incentives of energy charge for the corresponding load reduction.



(a) *(b)*

Fig. 25. Forecasting result of HV and LV customers in scenario 4 (summer) (a) Load reductions (LR) and contract capacity of load reduction (CCLR), (b) Incentives of energy charge for the corresponding load reduction.

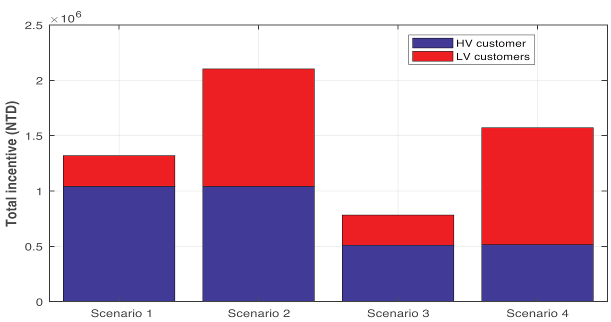


Fig. 26 Comparison of different scenarios

Table 2. Discussed cases for cost-benefit analysis.

	Hardware costs (NTD/customer)	Hardware lifetime (Year)
Case 1	50,000	2
Case 2	37,500	4
Case 3	25,000	6

NTD$50,000. Considering that the hardware cost may drop and its reliability may be improved in the future, as in case 2 and case 3 shown in Table II, the cost used in the simulation is the annually equivalent cost considering the interest rate of 3% and the life time of hardware for each case.

V. Conclusion

This paper has proposed a scheme to assess the potential of making profit for an aggregator to participate in the demand bidding in Taiwan. Techniques such as neural network and fuzzy logic system are employed for the forecasting of clearing price and load reduction, and the contract capacity of load reduction is decided through demand response algorithm. The simulation results have shown the evaluated effects for an aggregator to take part in two different types of DR and cooperate with two types of LV customer. The result has demonstrated the fact that the profit would be considerable when the aggregator signs reliable DR and aggregates single-house customers to execute aggregated DR.

However, there exists a different level of risk between reliable DR and aggregated DR. Based on the bidding rule, the aggregated DR has a larger tolerance for forecasting error than reliable DR, and it is verified in section 4. In addition, the cost-benefit analysis is performed to help the aggregator to make decision and evaluate the corresponding profit in a year. Finally, a correction process is proposed to improve the accuracy of the load reduction forecast for LV customers through realistic load-reduction data.

Acknowledgment

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By the time of publication the autors' CVs have not yet been provided

Efficiency of energy plantations

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***Abstract* — This paper presents an overview of the studies on creation and use of energy plantations. Their economic and environmental benefits are discussed. An economic-mathematical model for the efficiency analysis of energy plantations for fuel supply to remote settlements is briefly described. The results of the study based on this model are illustrated by an example close to the natural-meteorological and price conditions of the Irkutsk Region. Experimental calculations have showed that, at the existing prices, the supply of remote settlements in Siberian regions with fuel from energy plantations may be quite economically viable. The problem of selecting an optimal combination of biofuel from energy plantations and fuel sourced from other regions is discussed. The focus is made on three factors affecting the energy plantations efficiency: (i) the biofuel production, (ii) the delivered (traditional) fuel price, and (iii) the transportation factor depending on the configuration, required area of the energy plantation, and location of the economic center relative to the plantation. Special attention is paid to the problem of energy supply to the Baikal tourist and recreation zone.**

Index Terms - biofuel, renewable energy sources, fuel supply, ecology, energy plantations.

I. Introduction

At present, 81% of world energy production is based on non-renewable, exhaustible resources: solid (coal – 21%), liquid (oil – 38%), and gaseous (natural gas – 21%). Nuclear power plants produce 2% of the world energy, renewable energy sources (RES) – 18% [1].

Globally the RES potential exceeds manyfold the present-day level of energy consumption and may be regarded as the major source of energy production growth in the near future [2-3]. The main renewable energy sources are bioenergy and hydro energy [4]. According to the existing estimates, the bioenergy share equals 14% of the indicated 18% RES share. Other renewable energy sources (wind, solar, tidal) are of an essential local significance, but may hardly become substantial on the global scale [5].

Almost one third of the Earth population (about 2 billion people) still uses biomass in the form of wood [6] as the main energy source. Forests supply 87% of all the biomass used for energy production, agricultural products - 10%, and waste - the remained 3% [5].

Biomass is one of the most promising sources for energy supply to mankind owing to such properties as a substantial energy potential and sufficiently simple renewal both in a natural forest and on man-made energy plantations (where it usually grows faster).

There are two types of energy plantations according to the purpose of the produced energy resources. One of them is the motor fuel production from specially grown plants [7]. The other type to be considered in this paper involves plantations to cultivate wood intended for heating, household and industrial needs.

Biomass is most widely used to produce thermal energy in the household sector (8.9% of the above 14%), in the district heating system (1.2%), as well as for heating industrial premises (2.2%). In smaller scales, it is used for power production (0.4%) and in the transport sector (0.8%) as an alternative to hydrocarbon fuel [8].

Biomass may be an especially effective energy source for its supply to the settlements distant from large transport routes [9]. A high dispersion of settlements and low population density typical of the bulk of Russia's territory generate the need for the energy sources located to the energy consumers as close as possible to reduce transportation costs. By virtue of exhaustibility of hydrocarbons, and their steady price rise, heavy environmental problems caused by coal use, biomass from energy plantations should be regarded as a real prospect to solve the fuel supply problems in Russia. Its use in remote territories may provide their energy independence, increase ecological safety, and mitigate an adverse energy effect on the environment.

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II. Historical background

Since ancient times, wood has been the most important energy source. It was used to heat dwellings, cook meals, make weapons and household utensils. In the 19th century, fire-wood gave way to coal, and since the mid 20th century, oil and natural gas have become the main energy sources. Interest in wood as an energy source rose again in the 1970s as a result of the price shock in the world oil market [10]. Another fundamental reason for gaining interest in biofuel, generally, and in wood fuel, particularly, was aggravation of the environmental situation in the late 20th century because of an increase in harmful emissions into the environment due to the growth in the Earth population and production.

Since then, people have thought of searching for new types of primary energy resources, including renewable ones. The problem of using biomass and wood, in particular, for energy purposes has been studied intensively.

Search for the new biomass production technologies, analysis and optimization of the energy plantations efficiency have become the main avenues for research into energy plantations.

Among the studies on capability of energy forests, one should note those by Dr. V.A. Usoltsev. He is the author of more than 250 scientific works on testing and modeling biological reproductive property and structure of forest phytomass [11-12].

In Irkutsk (Russia), a team of researchers at the Siberian Institute of Plant Physiology and Biochemistry of SB RAS [13-15] develop an accelerated production of wood biomass for energy purposes. By the genetic engineering methods, they create plants which will naturally synthesize growth hormones in larger quantities than usually and, as a result, build up biomass much faster. This makes it possible to essentially reduce the biomass cost price. Another important component in the research is mathematical modeling of the entire process of biomass cultivation and stock on energy plantations for complex optimization of individual components of this process and selection of the means to improve cost efficiency of bioenergy plantations.

The problems of the cost efficiency of biomass production were addressed in a number of papers by foreign researchers [16-38]. O. Hellman, a Finnish mathematician, was the first to study this problem. In 1980, he analyzed the situation, when energy plantations consisted of several sectors [16]. The number of sectors equaled the number of years of wood ripening. Every year, in spring the forest was logged at one of the sectors, and in autumn it was cultivated there. Later, such a model was termed the Finnish model.

Further, O. Hellman evolved this model. In [17], he set the problem of searching for the optimal age to log forest. In 1982, O. Hellman studied the same problem for an energy plantation, on which new afforestation annually was unnecessary, as far as the system was self-reproducible [18]. Such a model cannot be viable because high risks of poor germinating ability of seeds. The absence of purposeful plantings implies chaotic growth of wood, which undoubtedly impedes logging.

In 1986, O. Hellman complicated the model including a possibility of cultivating several species of trees on one plantation [19]. His studies, however, did not consider specific features of cultivating different wood crops, possible variations in fuel production for reliable fuel supply from energy plantations.

In Poland and Sweden, E. Krasuska and H. Rosenqvist, M.Borzecka-Walker conducted large-scale research into assessing the cost price of the biofuel cultivated on energy plantations. They compared the production cost of the biofuel produced from such energy crops as willow, ribbon grass, hemp, silver grass and triticale [20-26]. The results of their research verify a higher economic feasibility of the willow cultivated on energy plantations, as compared with other energy crops.

Since 2006, the studies have been conducted in the Republic of Belarus to assess the cost-effectiveness of producing various types of biomass (willow, grain crops, perennial grasses) for energy purposes [27-32]. An interactive model was developed to calculate the benefit of cultivating energy crops and to evaluate the emissions in the environment. The economic and ecological efficiency of biofuel production from energy plantations was assessed by the example of willow.

In Russia, E.M. Romanov and E.M. Onuchin have been modeling the processes of biomass cultivation and harvesting. Their studies focus on developing the models for operation of bioenergy complexes to optimize technological processes of biofuel production in order to select the most effective technical solutions [33-38]. As a result, the quantitative relations between the parameters of bioenergy complexes and the technological parameters of equipment have been revealed.

Until today, little attention has been paid to a complex investigation into the entire chain of biofuel production, transportation and storage. The efficiency of fuel supply from energy plantations to remote settlements, whose supply with traditional fuels causes high transportation charges, has been insufficiently studied although it is topical for Russia.

The analysis of the efficiency of energy plantations for remote settlements should allow for the costs of the measures to be taken to reliably supply fuel from such sources. Previous studies did not consider effects of random factors that would influence the reliability of fuel supply. We addressed the issues of complex modeling and optimization of a set of measures on reliable fuel supply from energy plantations to remote settlements in [39-42].

III. Environmental benefits

The fuel produced from biomass may come from various sources. The main of them are waste of timber and farming industries, natural vegetation, and specially cultivated energy crops.

Debris and waste of timber and farming industries are ideal raw materials for biofuel production in terms of environmental protection. In actuality, however, their use often proves to be economically ineffective due to high harvesting and transportation costs, as well as unregulated organizational and legal issues concerning the use of logging debris and waste.

The use of natural forests as a biomass source for large-scale cutting down is undesirable, because they save biodiversity of flora and fauna, water resources, and protect soil from erosion.

The use of biomass from energy plantations has a number of environmental benefits compared to traditional energy sources [43]:

- mitigation of climate change problem;
- protection from soil erosion;
- reduction of water pollution;
- maintenance of conditions for the existence of forests, flora and fauna biodiversity.

Over the last 100 years, the mean air temperature on the planet has increased by 0.6°C [44]. For the daily temperature variation, this value is insignificant, but, for the global climate characteristics, this is too much. Combustion of traditional fuels leads to considerable emissions of harmful substances, first of all, carbon dioxide and methane. According to many scientists and politicians such emissions change the biosphere [45]. Replacement of traditional fuels with biofuel will contribute to mitigation of this negative effect [46]. The carbon dioxide is also released at plant biomass combustion. However, the plants release as many harmful substances as they absorb during their growth, which makes the carbon cycle closed.

Energy plantations may be located on the soils unsuitable for traditional agriculture, the places dividing the cultivated areas, or in the flooded territories [47]. Energy crops, like any other plants, reduce losses of nutrients from the soil.

Biomass has remained a major source of thermal energy, especially in the countryside. However, its harvest is often poorly arranged, logging of natural forests harms the ecosystem. Creation of special energy plantations may solve these problems [48].

IV. A Model for Analysis of the Efficiency of Energy Plantations

We analyze an energy plantation split into the number of sectors, equal to the vegetation period of trees (in years). In one of these sectors, the trees are logged in spring, and the cultivated saplings are planted out in autumn. All process stages, from soil preparation before planting to fuel harvesting, transportation, drying and storage, are sequentially considered, coordinated and optimized. At the same time, an optimal mix of machinery for fulfilling the entire spectrum of necessary operations is selected. The necessary construction of roads, warehouses to store fuel, greenhouses to grow saplings, number of employees, their salaries, taxes, demand for petroleum products are determined. The choice of timber species, its vegetation periods (number of sectors in an energy plantation), a set of agrarian-technical measures are optimized as well.

The cost-effectiveness of an energy plantation, options of possible solutions to individual problems in its creation, and also the price of its products may be determined using the following index of production costs:

$$C=I \bullet E_N+CO, \quad (1)$$

where CO is the annual current costs for energy plantation operation, million RUB/year;   is the investment in energy plantation creation, million RUB;   is the profit-to-investment ratio (in the examples below, it equals 0.12).

The profit-to-investment ratio may be regarded as a value equal to the annual interest paid on borrowed funds (bank and public loans, in the form of bond issuance proceeds) to create energy plantations, or as a value of expected dividends of the investment in the created enterprise, if it is formed as a joint-stock company.

The use of this index of production costs as a minimized criterion to select the options is naturally appropriate in the case of a long-term stability of conditions, under which the considered plantation will function. In the event of highly variable conditions (for example, an essential year-to-year increase in fuel demand of the given settlement), it is pertinent to apply other related indices, for example, discounted costs.

Although, the goal of the research does not include consideration of organizational and legal forms of the companies supplying fuel to remote settlements from energy plantations, we find it appropriate to make some suggestions on this point. To tackle the problems of fuel supply to remote settlements from energy plantations, it seems expedient to establish a non-commercial (but, undoubtedly, self-sustained) enterprise, for example, a municipal one. The enterprise is to arrange the entire production cycle: establishment of a plantation, cultivation, processing, and transportation to the biofuel warehouses. The prices of the biofuel delivered to the population and other enterprises should cover all the incurred costs. At the same time, the targets of the enterprise should not include profit earning, since it will have a monopoly on fuel supply to the given settlement. The settlement's authorities must control its operation.

Calculations on the model for analyzing the efficiency of energy plantations are performed by the step-by-step determination of the values of individual endogenous variables on the basis of varying exogenous indicators (harvest estimates, characteristics and prices of some kinds of machinery, salary levels, etc.). These calculations are presented as calculation techniques for certain components of the investment and current costs.

The considered model allows an iterative selection of an optimal mix of equipment, technologies in certain production process stages, an optimal plant species and time of its cultivation, other partial and system problems. Let us present two of them.

Minimization of the costs of fuel supply to settlements from energy plantations:

$$C(\text{x})\rightarrow\min \tag{2}$$

subject to

$$R(x)\geq Q, \tag{3}$$

$$x\in X, \tag{4}$$

where X is a set of the options of model variable values; $R(x)$ is the size of the annual biofuel production, tce (tons of coal equivalent); Q is the mean annual fuel demand, tce.

Selection of an optimal combination of using energy plantations and fuel sourced from suppliers in other regions:

$$C(x)+p_L L\rightarrow min \tag{5}$$

subject to

$$R(x)+L\geq Q \tag{6}$$

$$L\geq 0 \tag{7}$$

$$x\in X \tag{8}$$

where L is the volume of fuel sourced from suppliers in other regions, tce/yr; p_L is the price of this fuel, given the transportation costs, RUB/tce.

An emphasis should be placed on the following features of the model for analyzing the efficiency of energy plantations.

1. Nonlinearity of many relationships. For example, the relationship between the transportation volumes and the annual fuel production volume is nonlinear.
2. Discreteness of the values of certain variables, in particular, specifications and the number of different-type machinery pieces, number of workers, etc. The integrality conditions complicate the economic analysis, make it impossible to use such an important indicator as marginal costs. Therefore, in the calculations presented below, we apply a model modification, in which the integrality conditions are excluded. Such a modification provides the lower-bound cost estimates. Neglect of the integrality conditions may be justified by the possible partial lease of some kinds of machinery.
3. Uncertainty of the values of certain exogenous indicators (random nature of annual fuel demand; prices of machinery, petroleum products and lubricants) and necessary functional relationships for example, dynamics of woody biomass growth depending on certain weather conditions, etc.

The marginal costs are an important characteristic for economic analysis

$$MC(Q)=\frac{\partial\widetilde{C}(Q)}{\partial Q}, \tag{9}$$

where $\widetilde{C}(Q)$ is the minimum production costs for a specified biofuel volume $R=.Q$

The described model can be used to solve some partial problems in arranging the energy plantation operation, such as determination of an optimal age for the logged timber (number of sectors), selection of timber species that provide a set volume of biomass production at minimum costs, a comparative analysis of options for arranging and implementing agrarian and technical measures.

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V. Model testing

We present the results of a cost-effectiveness analysis for an energy plantation under natural, meteorological, and economic conditions close to those in the southern areas of the Irkutsk Region in recent years.

We consider the poplar plantations in the form of a circle with six sectors. The settlement is located in the circle center. Every six years, plants should be 4-5 m tall, and, in terms of 1 ha, yield about 10-15 tons of timber, which is equivalent to, approximately, 5 tce/ha [49]. In the calculations below, the price of the fuel delivered from other regions (considering transportation costs) is taken equal to 2500 RUB/tce. This assumption is valid if the fuel supplied from other regions is coal. The cost of coal from the largest deposits in the Irkutsk region (Cheremkhovo, Tulun, Zheron, Borodino) varies from 1200 to 1800 RUB/t, i.e. no less than 2000 RUB/tce. In terms of the costs of coal transportation to remote regions, its price equal to 2500 RUB/tce may be assumed for rough calculations.

If fuel is supplied to the settlement only from the energy plantation, then with a demand for fuel of 7950 tce (which approximately corresponds to a settlement with 6000 people), the plantation area should be a little less than 95.4 km^2, with a radius of 5.5 km. The required plantation area will vary proportionally to the change in fuel demand. In this case, the plantation radius, and correspondingly the average distance and the transportation volume in tkm will change nonlinearly. Therefore, the required investment and the current annual costs depend nonlinearly on the fuel demand. For example, for production of 7950 tce/yr, most of the investment (million RUB) falls on: (i) construction of roads (9.9), (ii) purchase of motor transport (9.8), (iii) purchase of tractors and logging equipment (6.6 each), (iv) construction of greenhouses (6.6), (v) purchase of equipment for sapling planting (0,06), and (vi) construction of warehouses (4,3). It is worth noting that, with a growth in fuel production, the investment in motor transport and construction of roads increases much faster than in all the others.

The greatest share in the current costs falls on remuneration of labor and taxes. For example, at the fuel production equal to 7950 tce/yr, the average annual costs of energy plantation operation are 6.7 million RUB/yr. Of this amount, the remuneration of labor is 5.2 million RUB/yr, and the costs of petroleum products and lubricants are about 1.5 million RUB/yr.

Relationship between the costs and fuel production volumes. Figure 1 presents this indicator obtained as a result of the model calculations. Starting with some argument value, the production costs are the increasing convex function of the biofuel production volumes. The costs of supply with the fuel delivered at a fixed price are the linear function of the consumption volumes. The Figure shows that the costs of fuel supply from energy plantations are lower than the costs of the fuel delivered from other regions, if the annual fuel demand is less than 13900 tce. The fuel sourced from other regions is more profitable in the case of large consumption volumes. However, it is valid only within the strict alternative: either supply with biofuel from energy plantations, or supply only with fuel delivered from other regions.

Figure 1 also illustrates that with an increase in fuel consumption, the difference between the costs of delivered fuel and the costs of the same fuel volume from an energy plantation rises at first and reaches the maximum value at a fuel consumption of 7950 tce/yr. At a further growth in the required fuel production from an energy plantation, this difference starts to reduce. It will be natural to assume that the indicated volume is "optimal" for an energy plantation, and its excess is inexpedient.

The data in Fig. 1 also show that energy plantations are unprofitable when they produce small volumes of fuel. This is explained by the availability of the minimum constant costs necessary for the plantation operation that do not depend on the fuel production volumes. In our example for a small settlement (no more than 200 inhabitants) with the fuel demand less than 250 tce/yr, creation of an energy plantation with a staff, machinery, special structures to maintain the plantation is inexpedient.

Selection of an optimal combination of energy plantations and delivered fuel. This problem can also be solved using the offered model. The selection logic is relatively simple: the fuel supply from energy plantations only is feasible for the volumes when the marginal costs of biomass production at energy plantations are below the price of alternative fuel, and when the marginal costs become equal to the alternative fuel price, it is feasible to supply with the delivered fuel (the "combined" option of fuel supply in Fig.1). Such a strategy obviously provides the least total costs on production of different volumes of fuel.

The fuel production volume at energy plantations, at which the marginal costs are equal to the price of alternative fuel, coincides with the above "optimal" volume for the given price of the alternative fuel. In the addressed example, the optimum volume of biofuel production is, as noted above, 7950 tce/yr, with the production costs of such a volume equal to 15.3 million RUB/yr. If this volume were covered with an alternative fuel, the costs would rise to 25.9 million RUB/yr. The difference of 10.6 million RUB/yr is the maximum effect of the energy plantation under the considered conditions, including the indicated price of the delivered fuel.

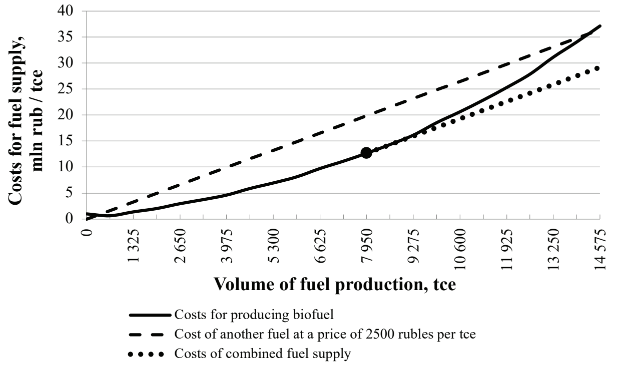

Fig. 1. Cost of delivered fuel and costs for biofuel production depending on the fuel production volume

The data in Fig.2 show that with a rise in the price of delivered fuel, the volume which makes it more profitable to supply fuel from energy plantations increases, and the optimal use of energy plantations rises with an increase in the delivered fuel price. Thus, with an increase in the delivered fuel price to 3500 RUB/tce (i.e. by a factor of 1.4), the optimal production volume increases to 10600 tce (by a factor of 1.3). The maximum effect of energy plantations, in that case, increases to 22.7 million RUB/yr (by a factor of 2.1). The delivered fuel price is essential for determination of rational scales of the energy plantations and their cost-effectiveness.

Transportation factor effect.

Creation of an ideal plantation in the form of a circle with a settlement in its center is not always possible. For example, settlements can often be located near the river or near another settlement. In other words, at the same volumes of fuel production from energy plantations, the

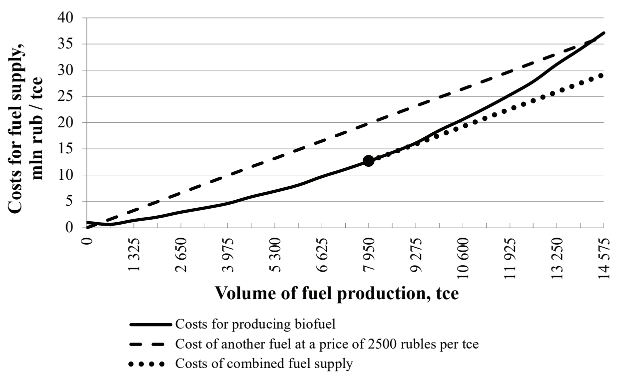

Fig. 2. Costs of biofuel production and the cost of fuel sourced from other regions at its varying price depending on production volume

transportation distance may essentially increase, which raises the production costs.

For example, with a fuel demand of 7950 tce and a double growth in the mean freight distance, the costs of biofuel production increase from 15.3 to 23.2 million RUB/yr (by factor of 1.5). The economic benefit will decrease from 10.6 to 2.7 million RUB/yr (by a factor of 3.9). If the optimal demand for fuel decreases from 7950 to 5300 tce (by a factor of 1.5), the maximum economic benefit will decrease from 10.6 to 6.8 million RUB/yr (only by a factor of 1.6).

The rise in the price of delivered fuel to quite a real value of 3500 RUB/tce with a double growth in the freight distance leads to the optimal fuel production at energy plantations being 5900 tce/yr. The economic benefit, in that case, equals 14.3 million RUB/yr.

The presented calculation results show that the supply of fuel from energy plantations to remote settlements may be fairly cost-effective even in Siberian regions. In addition, it is very important to consider territorial features of certain settlements, their natural and climatic conditions, and price situation.

VI. Expediency of using energy plantations for heat supply to the tourist and recreation zone of Lake Baikal

Over 1 million tourists and vacationers visit Baikal annually. This flow is expected to increase up to 5 million people in the nearest future. However, the region is not ready for such a flood of tourists. Many topical organizational and environmental problems have not been solved yet. Until recently, the main energy supply sources were:

- relatively inexpensive electric power;
- delivered coal (basically, only in sufficiently large settlements with special boiler plants);
- fire wood provided by logging firms and local population, including that from forest sanitation, from burnt places (by many estimates, this is one of the reasons for numerous forest fires).

Not long ago, relatively inexpensive electric power produced in the Irkutsk power system (mostly by hydropower plants) offset the cost-ineffectiveness of combined heat and power plants and provided low electricity rates for the population, which were almost three times as low as those in the adjacent regions. In the near future, the rate is expected to increase significantly (approximately by a factor of 3) in the Baikal near-shore areas of the Irkutsk Region. The rates will equal those in the rural areas of the adjacent regions and republics, which will make the large-scale electric power utilization for heating economically ineffective.

A wide use of coal in settlements, camp sites, and country houses in the territories adjacent to Lake Baikal is both expensive because of long distance transportation, and inexpedient due to environmental constraints. Lake Baikal is a UNESCO World Heritage Site, where the prohibitory regulations of the activities causing damage to the environment, are actively observed. It is hardly possible to provide expensive removal of carbon soot, carbon oxides, sulfur, nitrogen and other harmful emissions from coal combustion at low capacity boiler plants and, moreover, in household ovens.

There are several options of more environmentally acceptable fuel supply to the shore zone of Lake Baikal. These are: the use of natural gas, heat pumps, and timber cultivated on special energy plantations.

Natural gas supply to the Olkhon District is possible from the relatively close large Kovykta gas condensate field (Zhigalovo District of the Irkutsk Region). The distance to the latter equals about 300-400 km, depending on how it is measured: straightly or along roads. Since natural gas is the most environmentally clean fuel, its use at the Baikal shore is especially topical. According to the experts' estimates, there exists a high probability of relatively small gas fields in the Kachug District located closer to the Baikal shore (about 100 km). Based on the data of geologists, there may be small gas fields in the Ust-Orda National District, from which it is closer and easier to supply gas to the Baikal Natural Territory. These small fields may be quite sufficient to cover relatively small fuel demands in the Olkhon District and other territories at the Baikal shore even in the long term.

However, for some unknown reasons, the Kovykta field has not been used even for local needs for several decades. The built gas-fired boiler plants and gas pipelines in the settlements of Zhigalovo and Kachug have been standing idle. In the future, it is planned to construct gas pipelines to supply the Kovykta gas northwards to the export gas pipeline "Power of Siberia". Possibly, the supply of the Baikal shore with the natural gas from the gas field in the Irkutsk Region would be the best project, although it is not so scaled as export.

The use of heat pumps for the heating purposes of the local population and tourist camps located directly at the Baikal shore during wintertime is worthy of consideration. The Baikal water having a constant temperature (about +4°C) will be a heat-transfer agent in this case. Such a heating method is convenient because with a decline in the outdoor temperature, heat pumps will produce more thermal energy. At present, there are three heat pumps on Lake Baikal. Two of them successfully function at the Baikal Museum in the settlement of Listvyanka, the third was installed in the settlement of Tankhoy, but is not run because of the prohibition by the Prosecution Service due to the unresolved issue, whether the water abstraction for cooling in the heat pipes is harmful for Lake Baikal or not.

Thus, wood appears to be the main kind of fuel for the tourist and recreation zone of Lake Baikal, although the scale of its use is an unresolved issue. Campfires, bath houses, cooking over open fire require wood. To some extent, the needs for this fuel can be provided by reasonable use of forest resources in the adjoining territories, including forest sanitation. Undoubtedly, this must be accompanied by active afforestation (the "cut one tree – plant two" principle).

In the future, energy plantations should become the main firewood source to be specially created for this purpose. The areas particularly promising for energy plantations are those most attractive for tourism, i.e. the Maloye More shore (Island of Olkhon, and the Near-Olkhon Area, where the extensive Tazheran Steppe lies), the Bolshoye Goloustnoye area (the territory considered for constructing the so-called Baikal-City). All of these areas have huge land parcels suitable for energy plantations. It is worth noting that, currently, businesses are showing an increasing interest in establishing energy plantations in the Near-Baikal territories based on the results of this study.

VII. Conclusion

Biomass in the form of wood is one of the main energy sources and accounts for almost 14% of the world energy consumption. The use of wood produced at energy plantations may become rather promising for Russia due to the developed transport infrastructure.

Biomass has important environmental advantages over fossil fuels. Its application contributes to mitigation of the climate change problem, decrease in soil erosion, reduction in water basin pollution, maintenance of conditions for existence of forests, improvement in microclimate, to enhancement of the conditions for agricultural activity.

The presented results of the studies on the model for the analysis of the efficiency of energy plantations indicate that, in the existing price situation, energy plantations may be economically effective for fuel supply to the Siberian remote settlements, particularly, for fuel supply to the Baikal tourist and recreation zone. Consideration of environmental benefits of energy plantations in the monetary form, which was not addressed in this study, may provide additional benefits. In this case, one should also consider negative environmental effects of diesel fuel combustion by tractors and motor transport while maintaining energy plantations.

The obstacles to the use of energy plantations for fuel supply to the tourist and recreation zone are associated, strange as it may seem, with the nature protection legislation restricting industrial activity in the central ecological zone of the Baikal natural territory.

In the future, we plan to carry out an economic analysis of possible options and sub-options for energy supply to the tourist and recreation zone of Lake Baikal (including the mentioned gas supply, heat pumps, and other options).

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A Yandex Map-based geo service for visual analytics

Young researcher's note

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***Abstract* – The paper deals with the development of a visual analytics tool based on Yandex.Maps. The necessity to use geo services for energy research, in particular, in studying critical infrastructures with the help of visual analytics, is illustrated. Consideration is given to the specific features of geo services including their multilayer, multiscale and multiangular nature. The design of a new visual analytics tool based on Yandex.Maps is described. An important aspect of this development is the ability to import KML files. The implementation of the new tool prototype is demonstrated with a specific task. The additional possibilities of this tool are considered. The developed tool of visual analytics can serve as a decision support tool for analytical and predictive research in the energy sector to assess both the current state of the energy infrastructure and the conditions for the adoption of a potential development option.**

***Index Terms* – geovisualization, Yandex.Maps, Geo services, KML.**

I. Introduction

To study the energy sector as a critical infrastructure, it is advisable to use methods and tools of visual analytics and cognitive graphics.

Critical infrastructure is part of the civil infrastructure that represents a set of physical or virtual systems and means that are important for the state to the extent to which their failure or destruction can lead to disastrous consequences for the defense, economy, health care and the security of the nation.

Energy infrastructure is a set of physical or virtual systems that represents information about the production, generation, transmission, or distribution of energy.

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Visual analytics is understood as an opportunity to think analytically, supported by a graphical interface [1, 2]. In other words, it is a human-machine system where functions are distributed between a human and a computer [3].

Geo services found their use in presentation of a set of objects and groups of objects in the context of geospatial coordinates. They represent the services on the Internet intended for working with geospatial information. The Melentiev Energy Systems Institute (MESI) SB RAS is engaged in the research on visual analytics and cognitive graphics [4, 5], which has been recently conducted within the concept of "Digital Land" [6].

MESI SB RAS uses both traditional GIS, for example, [7, 8], and geo services of Google Earth [9, 10] to study and substantiate geospatial problems [5, 11, 12], including the research into the energy sector as a critical infrastructure [13].

II. Geo services: basic concepts

The use of geo services as tools for visual analytics offers a number of advantages. These are their multilayer, multiscale and multiangular nature.

Multilayer means the ability to arrange groups of objects in a form of layers on the map, which can be controlled separately. This advantage greatly expands the possibilities for analytics, in particular, it becomes possible to create samples from different groups of objects, build a hierarchy of objects, add additional layers necessary to analyze objects in the tasks related to the energy sector and energy systems.

Multiscale implies the ability to analyze and present the situation for different levels of display without distorting the information in a wide range of scales - from global to super-detailed.

Multinagular means the ability to position the observer's camera relative to the surface at any angle. This makes it possible to choose an angle that enables an object or a group of objects to be displayed in the most perceptible form or to focus on a certain part of the image.

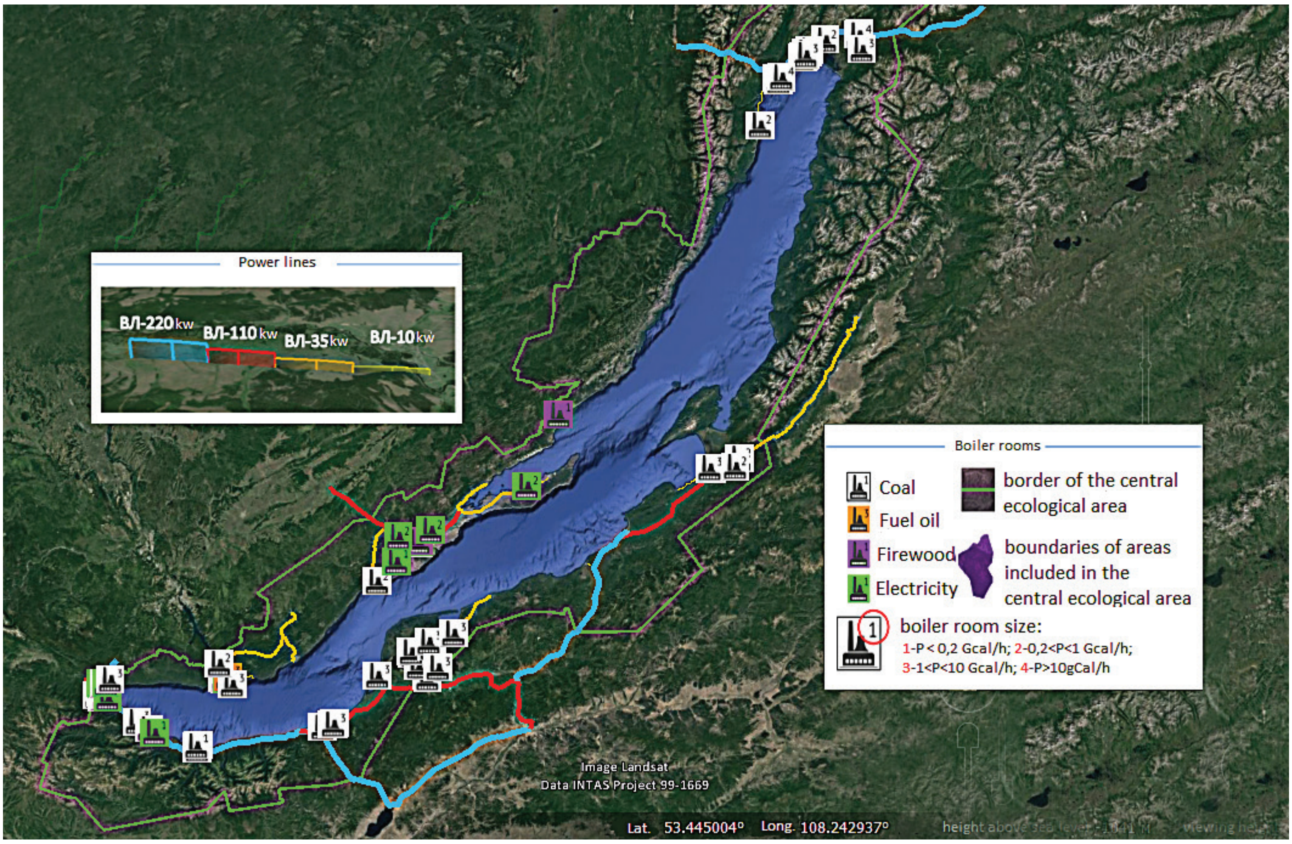

Fig. 1. Display of energy infrastructure of the central ecological zone of Lake Baikal with Google Earth.

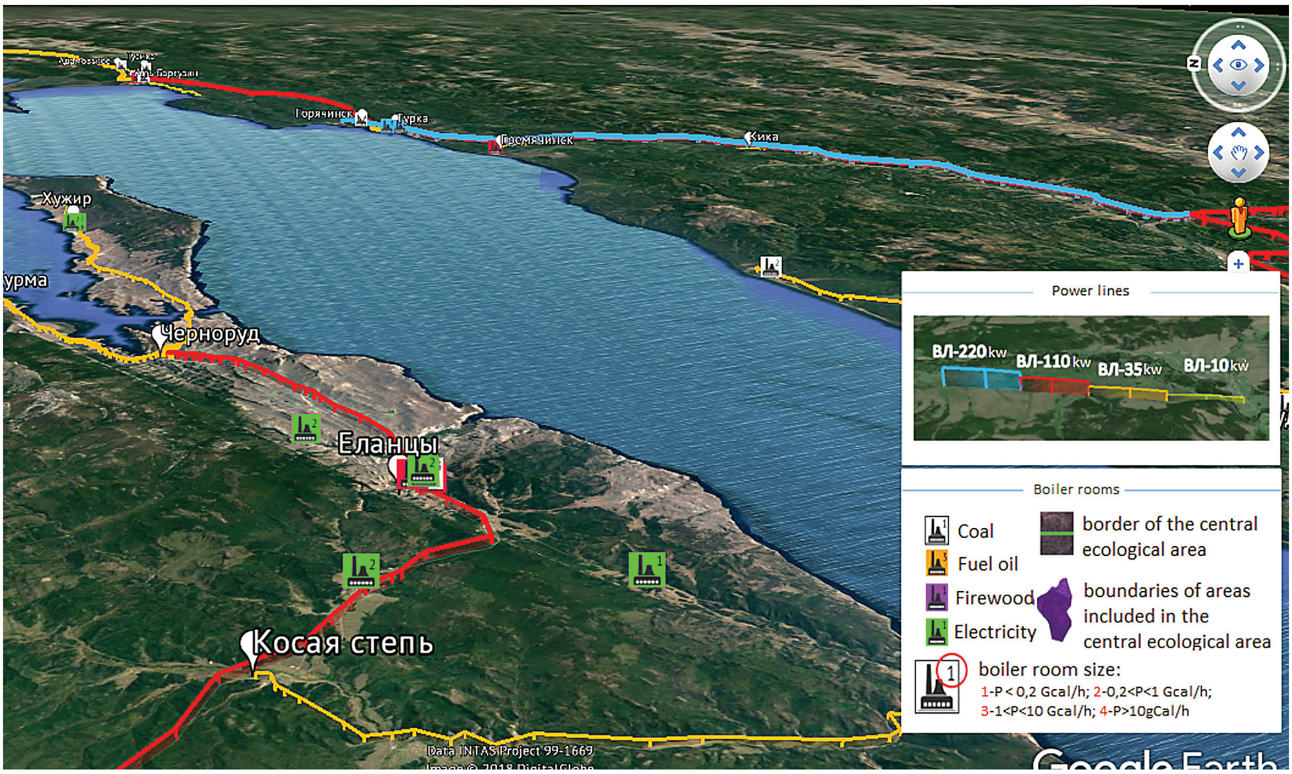

Fig. 2. An enlarged fragment of the central basin of Lake Baikal from a different angle.

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Installed capacity 0,8 Gcal/h
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Installed capacity 1,2 Gcal/h
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            </Placemark>


            <Placemark>
                <description>Boiler room №2, г. Бабушкин

Installed capacity 1,81 Gcal/h

ООО &quot;Комфорт&quot;</description>
```

Fig. 3. Part of importing KML file.

The above–described properties (Fig. 1 and Fig. 2) help organize the display of various information depending on the objective for any territorial level.

The Melentiev Energy Systems Institute SB RAS has developed a Geocomponent to work with geo services. It works through the Google Earth API with the KML geospatial data format [9, 10, 14] that was used to obtain these illustrations.

III. Design of a tool based on Yandex.Maps

Access to the Google Earth API was closed. This is why it was decided to use Yandex.Maps API to restore functionality. The goal was set to develop a visual analytics tool, similar to Google Earth, based on Yandex.Maps.

To achieve this goal, it was necessary to accomplish the following tasks:

1. Analyze the Yandex.Maps API capabilities to create a geo service based on it.
2. Develop a prototype of a visual analytics tool based on Yandex.Maps with the ability to import KML files.

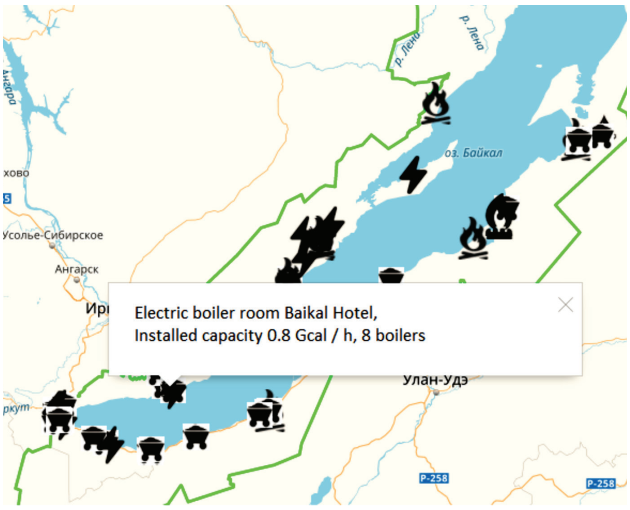

Fig. 4. Mapping of the energy infrastructure of the central ecological zone of Lake Baikal by the Yandex.Maps service.

3. Analyze additional features of Yandex.Maps for visualization and their use in this tool.

The Yandex.Maps service provides a convenient interface and technical support for integration with current research. It is used as a basis for the development of a tool to display geospatial information for energy research.

The Yandex.Maps service retains the basic principles, such as multiscale and multilayer nature of display. The service makes it possible to install a plug-in into your own application and work with it through the Yandex.Maps API.

IV. Implementation of a tool prototype

The prototype of the visual analytics tool based on Yandex.Maps was developed using HTML and JavaScript. This prototype provides the ability to import KML files using images.

The KML file specifies a set of features (placemarks, images, polygons, 3D models, textual descriptions, etc.) that can be displayed on maps in geospatial software implementing the KML encoding (Fig 3).

To load a map in KML, Yandex should process this file on the server side, because the Yandex.Maps API works like a JavaScript plug-in and does not provide local processing of KML and XML formats. In addition, you need to make sure that the Yandex.Maps API is able to load all images that are referenced in the KML file. Mapping of the energy infrastructure of the central ecological zone of Lake Baikal with Yandex.Maps service is shown in Fig. 3. This map shows the central ecological zone of Lake Baikal, the locations of boiler plants that use different fuels and their power output.

Moreover, the Yandex.Map API offers a wide range of functions for different kinds of visualization that will be added to the developed tool, including:

4. The use of panoramic pictures (360-degree images), which can be viewed in the interface of the map.
5. The creation of automobile, pedestrian and arbitrary routes.
6. The assignment of events for objects, i.e. a change in the parameters of the objects associated with timestamps and animation.
7. Visual clustering, i.e. collection of several placemarks in one area when zooming.
8. Filtering of objects by their parameters.
9. Forward and reverse geocoding, i.e. identification of an object by coordinates and vice versa.

V. Conclusion

The visualization of information by geo services through the use of realistic maps of the earth's surface (space and aerial photographs), in conjunction with the three-dimensional model of the globe, makes it possible to move to a new level of information presentation, owing to new opportunities for mapping geospatial information.

Therefore, it is the basis for the development of the tools intended to support decision making, both for the researcher, expert, and for the representatives of energy companies or authorities. The developed visual analytics tool can serve as a decision support tool for analytical and predictive research to assess both the current state of the energy infrastructure and the conditions for the feasibility of adopting a potential development option.

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Information Technologies for Building a Data and Knowledge Warehouse for Science and Technology Forecasting and Research of Critical Infrastructures

Young researcher's note

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***Annotation* – The paper is concerned with the application of the Open and Big Data technology in energy forecasting. The focus is made on the issues related to the creation of a data and knowledge warehouse for science and technology forecasting, and research of critical infrastructures.**

***Keywords* – big data, data and knowledge storage, science and technology forecasting, critical infrastructures.**

I. Introduction

Currently, the world is actively developing intelligent information technologies that support the innovative development of many industries and economic areas.

The importance of the intelligent energy technologies is undeniable [1]. As evidenced by the experience of many countries, these technologies are becoming the foundation for the development of electric power industry. In the USA, in particular, this is the main direction of improving the economy, China sees these technologies as a way of national strategic development. The European Union countries use innovative technologies as a basis for a new energy policy [2]. One of the components of the intelligent energy systems will be science and technology forecasting [3].

Science and technology forecasting implies the identification and preliminary assessment of trends in the development of science and technology, the prediction of major scientific and technical solutions capable of making quantitative changes in the overall science, technology and production potential of the country, in social relations, and world politics.

The information for science and technology forecasting will be formed on the basis of Open Data and Linked Open Data. The data will also be collected from such sources as state information systems that integrate the data on science and technology projects and developments (CITIS, RFBR, FIPS, etc.), as well as various commercial systems such as SCOPUS, Web of Science, RSCI, and Science Index [3,4].

An analysis of the information to be collected from the above-described sources can indicate general trends in the development of scientific and engineering thought [4, 5].The technologies and tools to be developed can be used to analyze the threats and assess the risks of cyber security incidents in critical infrastructures, including energy facilities [6].

II. Specific features of the data and knowledge warehouse for energy forecasting

Energy forecasting necessitates accumulating and analyzing a large amount of data. The more information is processed, the more accurate the forecasting results will be, as the increase in the data amount enhances the completeness of information and makes it possible to assess the reliability and consistency of the data obtained.

An exponential increase in various information in the modern world affects the creation of data and knowledge warehouse. The volume of information in the world increases by 30%, annually.

The data and knowledge warehouses are primarily designed for science and technology forecasting based on the analysis of heterogeneous, unstructured data sets of large volumes that need scale-out software and distributed computing for their effective processing and storage.

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The accumulated volume of data structured in the warehouse can be used to solve related problems in energy research: linked data on information technologies used at energy facilities can be used to analyze their cyber security.

III. Big Data Technologies

In this paper, the term Big Data means some technologies, tools, and methods for processing structured and unstructured data of large volumes, that allow distributed processing of information.

Principles of working with big data:

1. Horizontal scalability, i.e. with a rise in the storage volumes, the system should be able to support an increase in the number of servers;
2. Fault tolerance;
3. Data locality, i.e. data should be processed and stored at the same machine, otherwise the data transmission effort may exceed the data processing effort.

To solve the problem of data locality, Google proposed the MapReduce concept. MapReduce is a model of distributed computing, used for parallel processing of large amounts of information [7]. MapReduce assumes that the data are organized in the form of some records. Data are processed in 3 steps. The block diagram of this model is presented in Figure 1.

1. Map step. The input data of the problem to be solved represent a large list of values that are preliminarily processed at the step Map. To this end, the master node of the cluster receives this list, divides it into parts and sends it to the slave nodes. Then, each of the slave nodes converts the elements of the resulting collection to zero or several intermediate key-value pairs.
2. Shuffle step is unnoticeable for the user. At this step, the intermediate results are grouped.
3. Reduce step. At this step, the master node receives intermediate responses from the slave nodes and transfers them to the free nodes to perform the next step. The system sorts and groups all "key-value" pairs by key and then, for each pair "key-group of values", collapses the values often into one value or an empty list. The obtained result is a solution to the originally stated problem [7, 8].

One of the possible solutions for organizing distributed big data storage and processing is the NoSQL class databases. They come in 4 types:

1. A key-value store. It is a database that uses the key to access the value. The examples of such stores are Berkeley DB, MemcacheDB, Redis, Riak, and Amazon DynamoDB.
2. A Bigtable storage. In this storage, data are stored as a sparse matrix, with its rows and columns used as keys. The examples of databases of this type are: Apache HBase, Apache Cassandra, Hypertable, SimpleDB.
3. A document-oriented database. It serves to store hierarchical data structures. The examples of this type of databases are CouchDB, Couchbase, MarkLogic, MongoDB, eXist, Berkeley DB XML.

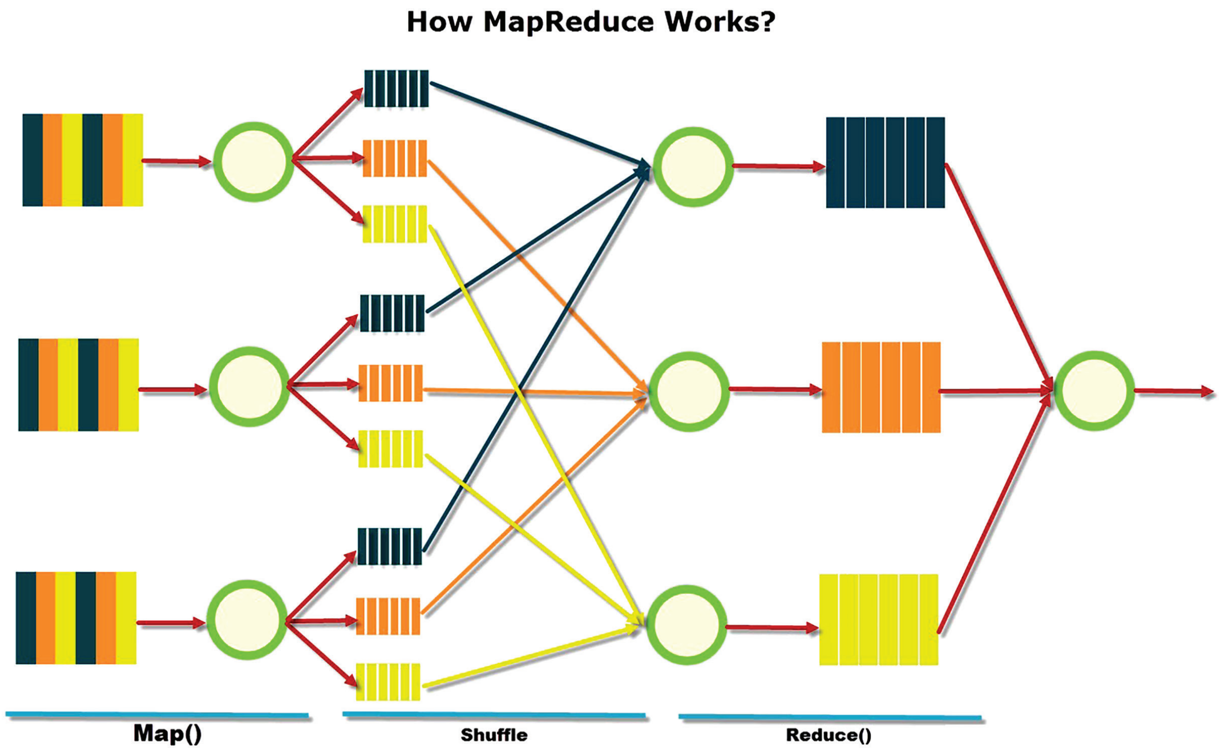

Figure 1. The MapReduce model (http://blog.sqlauthority.com).

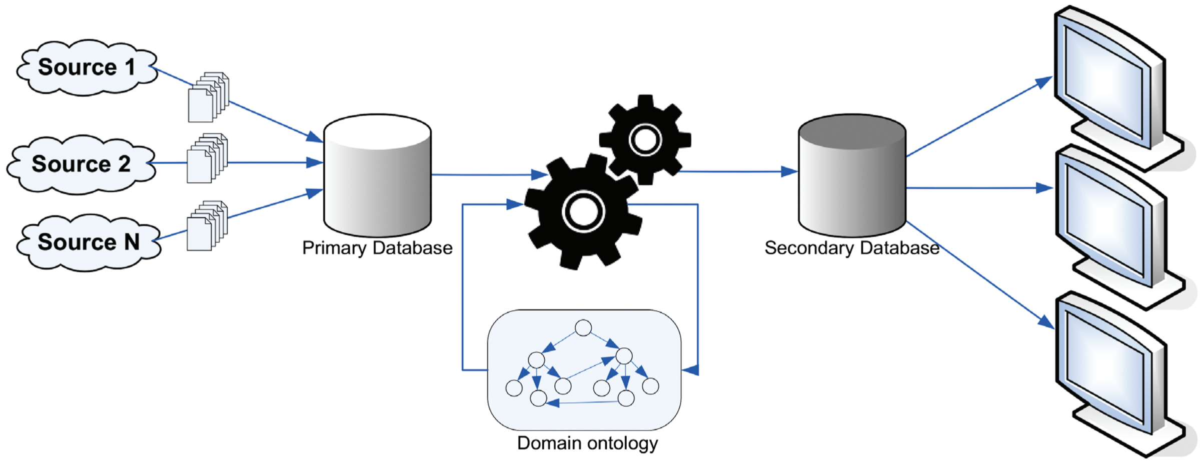

Fig. 2. The proposed architecture of the system.

4. A graph database. It is used in tasks with the data having a large number of links (social networks, fraud detection). The examples of the graph databases are: Neo4j, OrientDB, AllegroGraph, Blazegraph (RDF-storage formerly called BigData) [7].

IV. The proposed architecture of the system

The architecture presented in Figure 2 is proposed to implement the system of science and technology forecasting. The documents (articles, monographs, etc.) and relevant metadata are extracted from the resources specified in advance, such as RINC, Scopus and others. Based on the extracted documents, the primary document storage is formed. Then, a predetermined ontology of energy terms is used to make a semantic analysis, and the obtained results are transferred to a graph database. After this step, the results will be available to the end user.

V. Conclusion

Nowadays the Big Data technologies make it possible to store and process the information distributed on many servers and computers. The proposed solution will support an increase in the storage size in accordance with the amount of the information required for the tasks of science and technology forecasting in the field of energy and the study of critical infrastructures.

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