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Contents

Development, Modeling, and Testing of a Unified Controller for Prosumers Connected to 0.4 kV Voltage Level Grids. Part I: Modeling and Test Bench Assembly

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***Abstract* — The increasing use of distributed generation and energy storage units calls for changing the control methods for distribution grids. It is known that uncoordinated control of multiple "prosumers" (power grid consumers who can also generate power) can lead to unacceptable grid operating conditions. In the present two-part study we present the concept of a unified controller (UC) for prosumers at a 0.4 kV voltage level grids that can prevent the grid entering into undesired operating conditions. In the first part of the study, we present a problem statement with illustrative examples and then proceed to describe the principles of operation of the unified controller (UC). We then describe the laboratory test bench that was assembled specifically to validate the controller performance under real-life conditions. We describe the general arrangement of the test bench and the measurement system required to perform the corresponding controller testing.**

***Index Terms*: prosumers, inverters, distribution grids, control of multiple energy sources.**

I. Introduction

Conventional distribution grids have been "passive" parts of power systems: those distribution feeders always served a purpose of conducting a one-way power flow from substations to loads. However, the recent trends of increasing penetration of distributed generation and energy storage units have dramatically changed the behavior patterns of loads [1]. Now being able to both consume and generate power (and change the operating conditions in an automated way), the loads become the so-called prosumers – active participants of distribution grid operation. Typical examples of load types are households with either PV panels or storage units or electric vehicles, or with any combination of those.

Prosumers are typically controlled locally according to their own goals, although it is possible to implicitly influence their operation, for instance by sending some electricity price signals [2, 3]. Until the number of prosumers connected to a distribution feeder remains small, there is no significant impact from their side on the distribution grid operation. However, once prosumers' contribution to total power flow becomes considerable, their uncoordinated actions (either according to their own control logics, or in response to some grid parameters) might lead to unacceptable grid operating conditions. One of the most prominent examples illustrative of such a behavior is the uncoordinated charging of a set of electric vehicles on a distribution feeder. The problem of coordinated charging of a set of EV's connected to the same distribution feeder has already become well-established one in power engineering, attracting a lot of research [4–7].

Another classical example is a distribution feeder with high penetration of renewable sources (typically, PV panels). It is well known, that under high generating conditions, the voltage level on certain buses can become unacceptably high [8]. There have been a vast number of papers on voltage control by PV panels, with most of the results revolving around some reactive power control schemes [9–11]. Interestingly, it was recognized early enough, that due to considerable R/X ratios in distribution grids, constant voltage profile and minimization of losses in the grid cannot be simultaneously achieved. This is contrary to the transmission grids case, where two problems are almost equivalent. Therefore, for distribution grids, there exists a trade-off between voltage control goals (e.g., achieving a flat voltage profile or regulating voltage on certain buses) and reduction of power losses (or limiting

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the power flow through the feeding transformer) [12].

The problem of prosumers control has been one of the most widely addressed in the literature during the last decade. There is a vast amount of findings for both coordinated and uncoordinated control, as well as comparison of those two approaches and discussion of possible trade-offs. As a general rule, with the increasing share of prosumers connected to a distribution grid, the advantage of coordinated control over uncoordinated one grows, and after a certain point, uncoordinated control proves inefficient, due to excessive constraints needed to guarantee stable grid operation under a wide range of the system parameters. Most of the available results in literature are mainly control approaches and algorithms, which are tested by simulations, with the vast majority of methods dedicated to optimal real and reactive power dispatch. In such studies, power flow problem is solved, and prosumers are represented as ideal power sources or loads (for both active and reactive power). Details of control of power electronics devices are rarely taken into account, which is justified in most cases.

In the present two-part study we present a model of a new unified controller for prosumers in a distribution grid. The goal of the controller is to perform a coordinated control of a number of prosumers in order to guarantee stable and secure grid operation under different conditions. The motivation behind the controller development is the fact that prosumers are becoming more widespread in today's power grids, and very soon their uncoordinated control (or absence of control) will lead to reduction of the grid security. We also present the results of laboratory testing of the proposed controller on a realistic test bench representing a distribution feeder. The controller operation is tested on a system with two "passive" (although controllable) loads, and three prosumers, represented by inverters capable of operation in 4 quadrants, which are also developed and assembled in our laboratory. Compared to commercially available ones, our inverters have "open control architecture" – the control system is fully accessible to us, which is required to test a number of scenarios of the unified controller operation. In this first part of the study we present a background of the prosumers' control problem, propose the model of the unified controller, and provide a description of the laboratory test bench, including upgrades in the measurement system that were done specifically to perform the controller testing.

The rest of the study is structured as follows. In Section II we provide a problem statement and give an illustrative example where uncoordinated control of prosumers can cause unacceptable grid operating conditions. In Section III we provide a description of the unified controller and present its general scheme. Section IV is dedicated to a description of the laboratory test bench that is used for controller validation, together with the description or the measurement system that was installed specifically to perform the testing.

II. Problem statement and an illustrative example

In this section we provide a description of the general problem statement of the unified controller. In order to demonstrate the practical significance of the problem we also provide a motivational example of a distribution feeder that can potentially run into unacceptable operating conditions when prosumers adjust their controllers independently.

In order to illustrate the problem of uncontrolled (or controlled in an uncoordinated way) prosumer behavior, let us consider a simple two-bus system shown in Fig. 1. Such a system can be used to represent a distribution grid where all the loads are aggregated as a single load bus. This is reasonable if one is mostly interested in the effect of the prosumers' control on the total current drawn from the grid. We use this aggregate system to derive some closed-form expressions that can illustrate the type of controls that prosumers can execute and that can lead to an unacceptable operating point of a distribution grid. The voltage difference ΔV between the infinite bus and the load bus, i.e., $\Delta V = V - V_0$ in its linear approximation (which is rather accurate for distribution grids) is:

$$\Delta V = -\frac{1}{3}\frac{RP + XQ}{V_0}, \qquad (1)$$

where P and Q are the aggregate active and reactive power loads, and R and X are the resistance and inductance of the line connecting the substation and the aggregate load. We note that the formula (1) represents the linear approximation and is very convenient for control design. However, we also note that unless the feeder is very long, formula (1) can be remarkably accurate over a wide range of loading levels.

From the formula (1) it can be inferred that if a prosumer is injecting to the grid certain active power P_g (on top of its regular loading level), then an additional control can be executed to consume the corresponding amount of reactive power equal to $Q_c = RP/X$ in order to compensate for any voltage deviation on the prosumer bus as caused by its active power injection. This can be arranged either directly by setting the prosumer power setpoints to satisfy this ratio or by setting certain voltage-reactive power droop characteristics with a steep enough response. In either case, the injection of the active power by prosumer leads to its increased consumption of reactive power, which is done intentionally in order to improve the voltage profile in the feeder [12].

Suppose that the system of Fig. 1 corresponds to 5 loads of the overall power consumption of P = 75 kW (15 kW each) and Q = 37.5 kVAr. This corresponds to 15 kW of active power per load and the Q/P ratio of 0.5, which is a rather realistic assumption. Let us also assume that the aggregate load is connected to a substation by a 200 m long line with the A-35 type wires with active resistance of R = 0.78 Ω/km, and reactance of X = 0.27 Ω/km – which is again, a realistic assumption. In this case,

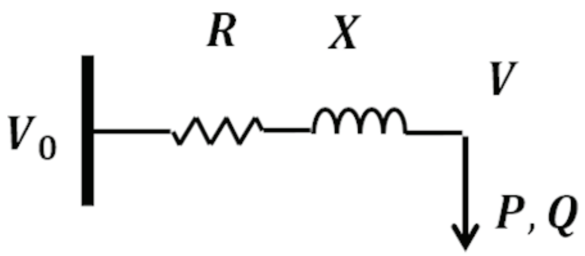

Fig. 1. A simple two-bus systems.

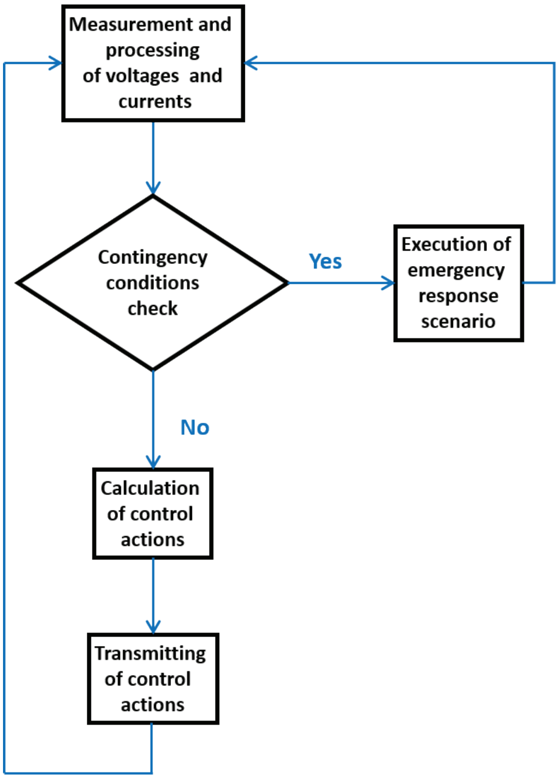

Fig. 2. Flowchart illustrating the operation of the unified controller for prosumers.

the phase-to-ground RMS voltage drop at the load bus is approximately $\Delta V \approx 20V$ which is on the boundary of the acceptable voltage deviation value. The RMS value of the current running through each phase is then 139.8 A, which is well within the limit of 172 A for the given type of wires.

Suppose now that two out of the five loads are prosumers that additionally inject 15 kW of active power each, i.e., effectively cancelling their active power consumption. In this case, if the simultaneous reactive power control is activated, each prosumer has to additionally consume 45 kVAr of reactive power in order to keep the voltage profile nearly the same as it was before the active power injection. This will lead the substation RMS phase-to-ground current to grow to nearly 224 A, which is well above the allowed limit of 172 A.

Such an example, although somewhat exaggerated, clearly demonstrates how the uncoordinated control of prosumers can lead to unacceptable distribution grid operating conditions. In the example above we assumed that only two out of five loads become prosumers, and it is obvious that even at this rather low level of penetration of prosumers the problem can become quite acute when there is no interference from a distribution grid operator.

There are a number of options to cope with the potential problems caused by uncoordinated prosumer controls that were illustrated above. One option is to set certain limits to prosumer active and reactive power generation; however, these limits will become overly conservative with the increasing share of prosumers in the grid. This will lead to severely sub-optimal operation states for the distribution grid. Another possibility is to introduce a certain level of coordination in controlling prosumers, which will be executed using additional knowledge about the grid parameters and also using the measurement data. Such a centralized control is not necessarily realized in the form of fixed setpoints specified for every prosumer but can also be executed by updating the limits on power outputs for every prosumer based on the existing grid conditions. In either case, a certain centralized controller is required that can leverage the information about the grid parameters and operating conditions in order to make decisions on the allowed prosumer setpoints.

III. Unified controller for prosumers

In this section we present the structure and operating principles of our unified controller for prosumers at 0.4 kV distributions grids. The controller is intended to execute coordinated actions over a set of prosumers in order to guarantee the secure and optimal operation of the distribution grid. As was illustrated in the previous section, fully decentralized control of prosumers cannot guarantee the secure grid operation under all scenarios, therefore the unified controller needs to perform the calculations over the grid model and update the control actions in order to satisfy all the constraints. Of course, many implementations of such a controller are possible depending on the available measurements, computational resources, communications system, etc. In this study we present a controller with a comprehensive set of possible functions ranging from a simple power setpoints update to fast real-time reassignment of the control modes for prosumers' inverters, allowing for seamless transition from grid-connected to islanded operation and back.

The flowchart describing the unified controller operating scheme is given in Fig. *2*. The controller collects the measurements of the voltages and currents from all the grid nodes (where measurements are available) and first checks whether the grid is in a contingent state. If there is no contingency, then the calculation of control actions for all the prosumers is executed and transmitted to the prosumers that are connected to the controller. The procedure is run continuously, with a certain time resolution, which is 50 μs (corresponding to the 20 kHz refresh rate) in the case of this study. We note that such

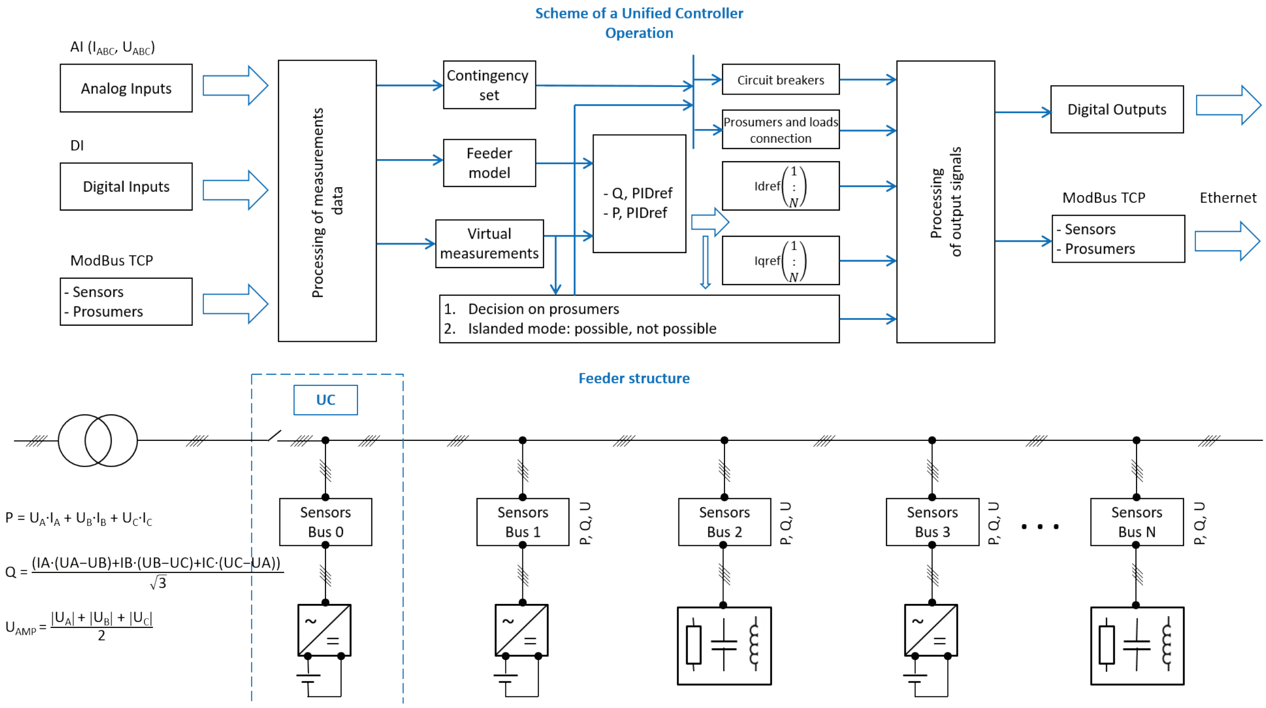

Fig. 3. Flow diagram of a unified controller operation and the controller placement in a distribution feeder.

a fine resolution is not a mandatory requirement, and it is possible to implement the controller operation at a lower resolution. However, execution of certain functions, such as a seamless transition of the grid to islanded operation, cannot be performed using controller with low time resolution. In the present study, our aim is to demonstrate a wide range of controller capabilities, so we use the high resolution of 20 kHz. Development of controllers meeting less strict requirements, or even a controller with some elaborate scheme where different time-steps are used for different purposes is a subject of further research.

Fig. ***3*** represents the structure of the unified controller (UC) and its place in the feeder. The controller can receive both analog and digital signals from measurements across the feeder: any possible combination of measurements can be used and the number of input channels should be adjusted depending on a particular feeder. The controller also has the input channels to accept signals over the ModBus communications protocol. In our case, most of the feeder buses were sending the measurements over this protocol. All the input data are then processed and readjusted for a set of measurements having the same time resolution. The measurements are then fed into a feeder model that runs in real-time – in our case we used the OPAL-RT module, however, different options are possible, depending on the purpose of the controller. Likewise, different levels of modeling details can be realized depending on the control goals. Since our goals in the present work were to perform a broad range of controller functions, we used rather detailed models of inverters for our controller. Contingency set check is also run in order to verify the feeder operation state: if a contingency is detected, then the control actions are selected from a dedicated set. In the absence of contingency, the controller is making decisions for prosumers' setpoints on a continuous basis and sends the corresponding signals to every prosumer under control.

After the input data is processed and fed to the feeder model, the decisions are made on the control actions: in our case the time resolution is 50 μs, which corresponds to the frequency of 20 kHz. The control actions include both continuous and integer variables. The former are the power setpoints for prosumers, while the latter are the on/off decisions as well of the grid-forming/grid-following decisions. Once the output signals are generated, they are sent to the prosumers over the ModBus communications protocol, however, other options are also possible. The controller is supposed to be placed at the feeding substation, with certain communications infrastructure available to transfer the measurements from the feeder buses to the controller. The bottom part of Fig. ***3*** represents the flow diagram of a feeder with the controller placed at the substation and sensors located at each prosumer and load bus, however, we note that flow diagrams with sensors only at some of the buses are also possible.

In order to test the controller operation under different scenarios, we have assembled a dedicated test bench with high-resolution measurement system and a number of inverters that represent prosumers. The next section describes the test bench in detail.

IV. Test bench assembly

In what follows we provide a description of the comprehensive laboratory test bench developed by us to experimentally validate the operation of our unified

Fig. 4. A smart grid test bench at the laboratory of energy systems at Skoltech. Every rack contains a load (either linear or nonlinear) or generator (of different types).

controller. We first describe the existing facilities: a "smart grid" test bench available at the Skoltech laboratory, and then provide a description of additional measurement systems that were installed for extensive testing with power electronics components.

A. Smart grid laboratory test bench

The smart grid test bench represents a physical model of a distribution grid with the possibility of connection of up to 3 individual loads, 3 individual generation sources (namely, storage, PV, and wind), and a possibility to change the effective resistance and reactance between the grid buses. The effective lines are represented by 3 segments with the corresponding resistance and reactance of 0.5 and 0.314 ***Ω***, 1.0 and 0.314 ***Ω***, and 1.0 and 0.628 ***Ω***, respectively, that can be combined in arbitrary arrangements. An image of the test bench is presented in Fig. ***4*** where only a part of the bench is shown, and every rack corresponds to either a load or generator.

The test bench measurement and control system is a SCADA system that collects measurement of RMS voltage and current from every bus of the test bench with a time resolution of 1 Hz. The output of such a system is presented in Fig. ***5***. Likewise, any control actions, such as load change, are also executed with a resolution of 1 Hz. Such a slow monitoring and control system is not adequate for controlling fast power electronics devices, therefore, for this purpose the test bench needs to be upgraded with a much faster measurement and control system. On the other hand, a certain trade-off is needed between the measurement system speed and its resiliency and cost. Thus, having very fast measurement system at every bus not only proves expensive but is also demanding in terms of the computational resources. For our specific purposes of a unified controller operation, at least one point in the grid (connection to the feeding substation) should be equipped with the high resolution (20 kHz) measurement system.

B. Measurement system

In order to collect the measurements of voltage and current and execute control actions at a sufficiently fast rate, the smart grid test bench was significantly upgraded by adding a fast-acting measurement system. The measurement system contains two types of measurement devices: measurement boards with fast current and voltage sensors that measure phase voltages and line currents at the 20 kHz resolution, and Power Quality Analyzers that provide the measurements of RMS of voltage and currents with the resolution from 5 to 50 Hz.

Fig. 6 shows the single-line diagram of our test bench with

Fig. 5. A screen capture from the SCADA system of the test bench. It is clear that only the RMS values of voltages and currents can be seen.

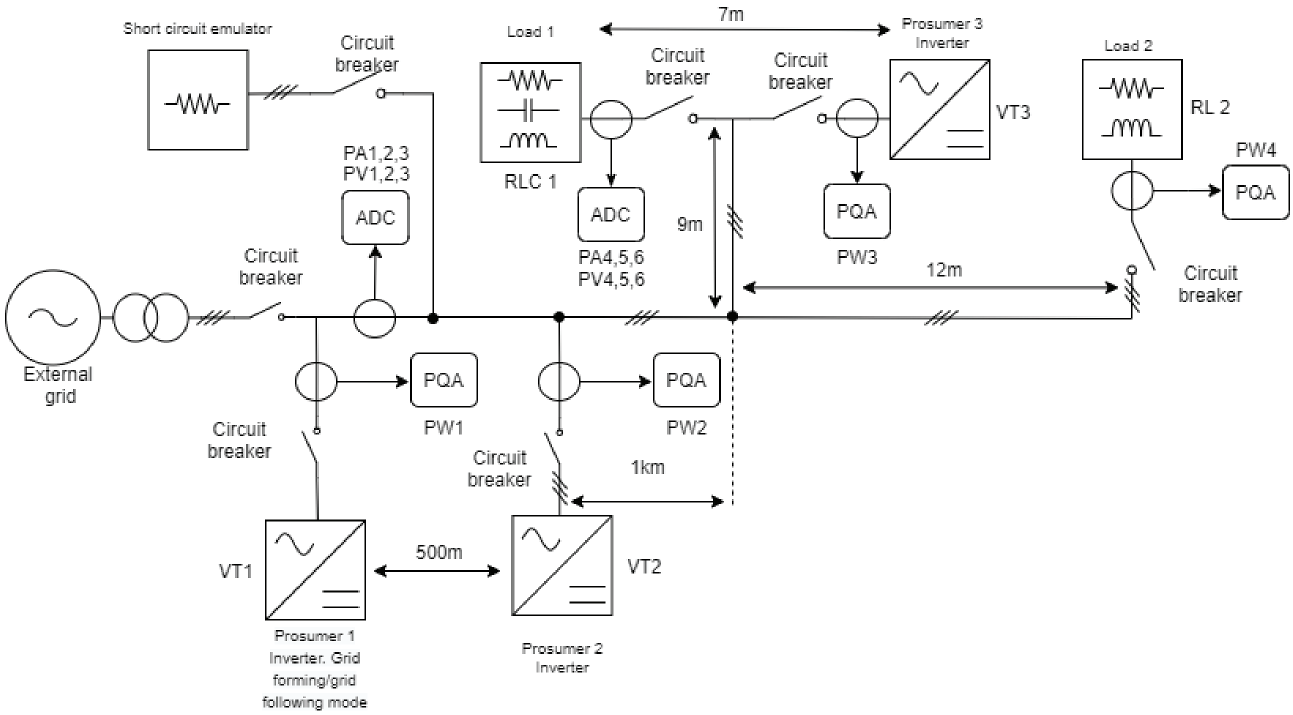

Fig. 6. Single-line diagram of the test bench with loads, prosumers, and the measurement system mounted.

Fig. 7. High resolution sensors mounted on a rack and plugged-in to the smart grid test bench.

connected loads, prosumers, and the measurement system. There are two constant impedance loads connected to the system, and three prosumers, each of which is represented by an inverter of our own design and assembly. Each inverter can operate in 4 quadrants and is also capable of operating in both grid-following and grid-forming modes. The fast (20 kHz) measurement units are installed at two points – at the feeder entrance and at the point of connection of Load 1. These units are denoted as "ADC" (analog-to-digital converter) in the diagram of Fig. 6. We note that the analog signals from these sensors go directly to the OPAL-RT real-time machine. Each unit is equipped with

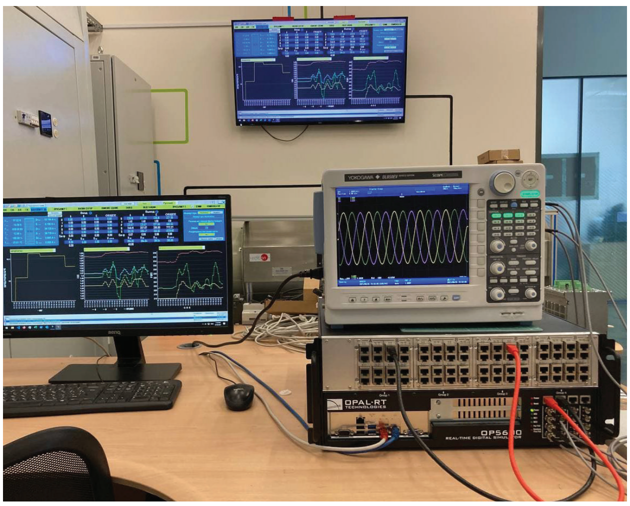

Fig. 8. Oscillograms of an AC-voltage signal from the operation of the test bench collected using the high-resolution measurement system.

4 LEM LV 25-P voltage sensors and 4 Honeywell CKSR 15-NP current sensors. Thus, there is a total of 16 analog signals going to the OPAL-RT machine. Fig. 7 shows the fast measurement unit connected to the test bench.

Another set of measurements is denoted as "PQA" (power quality analyzer) in the diagram (Fig. 6), they measure RMS voltage and current with a resolution of 5–50 Hz, which are processed by an OPC Modbus Server that also sends the (digital) signals to the OPAL-RT machine every 10 ms. Taking into account that the time resolution of the PQA units can be as low as 5 Hz, the overall accuracy of the measurements from the corresponding points is also limited by this number, which is still significantly better than the initial 1 Hz resolution of the SCADA system. Together with the fast measurement units described above, this system of measurements is sufficient for the purposes of validation of the algorithms of the unified controller for prosumers. Fig. 8 shows an example of oscillograms measured at the test bench feeding line.

V. Conclusion

In this first part of our two-part study we have presented a description of a unified controller for prosumers and a laboratory test bench that was assembled for experimental validation of the controller operation. We have also presented an example of a distribution grid operation without a coordinated control that can lead to unacceptable operating conditions, thus the motivation for development of a unified controller was demonstrated. Our controller setup is developed for execution of a broad range of actions, therefore, in our particular case the controller is rather demanding in terms of computational power and measurements resolution. We note, however, that less demanding controller setups are also possible, although at the expense of the controller capabilities and performance. The practical choice of controller capabilities will be a subject to some optimization over the required capital expenditures for measurement and communications infrastructure and the particular needs of the feeder. In the second part of this two-part study we will present the results of the extensive testing of the performance or our unified controller.

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Development, Modeling, and Testing of a Unified Controller for Prosumers Connected to 0.4 kV Voltage Level Grids. Part II: Experimental Validation

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***Abstract* — In this second part of the study we present the results of a laboratory testing of the performance of our unified prosumer controller. Complex multi-timescale dynamics of power electronics devices makes it crucial to perform the experimental validation of our findings [1, 2]. First, we describe the control system of inverters that are used in the testing. These inverters were designed and assembled by us specifically to have extended control capabilities compared to commercially available inverters. In fact, we have the full access to any of the control loops of those inverters – from the power stage and pulse-width modulation (PWM) realization to grid synchronization and slowly acting power control. We then proceed to the laboratory testing of the controller performance. First, we test the power setpoints control for prosumers in a closed-loop setup when the unified controller reassigns the setpoints for prosumers following a sudden change in the loads of the feeder. Next, we proceed to a more challenging task of a seamless transition of the grid into islanded operation. To this end, upon detection of the event of disconnection for the main substation, the unified controller assigns one of the prosumers to transition to a grid-forming mode. Thus, there is no interruption of the power supply after disconnection from the main grid. Finally, we demonstrate the reverse transition when the islanded grid is connected back to the feeding substation.**

***Index Terms*: prosumers, inverters, distribution grids, control of multiple energy sources.**

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I.Introduction

Coordinated control of prosumers connected to a distribution grid can offer a lot of advantages from the point of view of the grid operating conditions. A number of advantages can be brought by coordinated control to grids with low to moderate prosumer percentage: better voltage regulation, minimization of power losses, avoiding line overloads, to name a few typical examples. For the grids with a high percentage of prosumers among the loads, coordinated control can become a necessity – the uncoordinated actions of multiple prosumers will often drive the grid into unacceptable operating states. Moreover, for grids with enough generation capabilities to satisfy the load, it is possible to perform a transition to islanded operation, when the feeder disconnects from the main grid, while still operating and feeding all the loads. In this case, at least one of the inverters should switch into the grid-forming mode, and this can be realized with the help of a unified controller.

Although there are a lot of different control algorithms proposed in literature, most of the results concern some optimal energy management systems with the addition of reactive power dispatch. The validation is usually done by simple power flow type simulations, without taking into account the complex nature of the prosumer power electronics interfaces. In this second part of the study, we present the results of the laboratory testing of our new unified controller for prosumers. We perform the tests based on the smart grid laboratory setup, supplemented by additional high-resolution measurement system and custom-made inverters connected to the test bench. This type of experimental validation provides an ultimate way of testing the validity of our controller design. The test bench provides a very realistic replication of a real-life distribution feeder, and experimental results serve as the first step towards commercial-scale implementation of the unified controller.

For our testing purposes, we have pre-selected a number of specific scenarios, ranging from simple

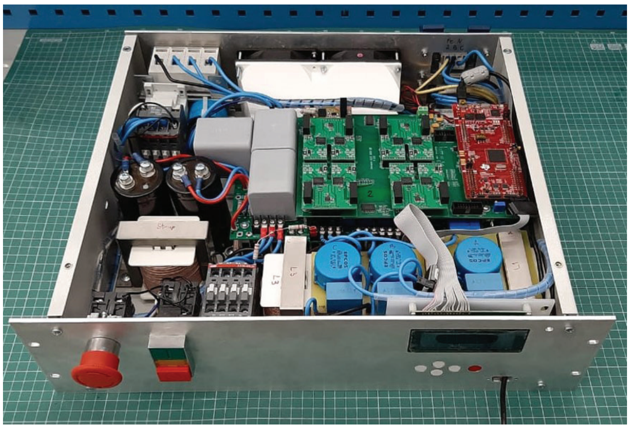

Fig. 1. A photographic image of the inverter developed and assembled in our laboratory for validation testing of the unified prosumer controller.

power setpoint adjustments to fast transitions between grid-following and grid-forming modes for inverters. Three inverters with fully "open" control system have been developed and assembled specifically to perform the experimental validation of the unified controller. In Section II, we provide a detailed description of the inverters, including hardware design and control loops implementation. Section III then proceeds to describe the actual testing. Two complex test scenarios have been investigated. The first one focuses on an automatic change of power (both active and reactive) setpoints of prosumers following a sudden load change in the feeder. The second one is dedicated to a seamless transition to islanded operation and back to the grid-connected operation without interrupting the load supply. This is done by a fast action of the unified controller that sends a signal to one of the prosumers to switch between grid-following and grid-forming modes of operation.

II. Inverters used for representation of prosumers

In this section we provide a description of inverters that were designed and assembled specifically to be used in laboratory tests, including the validation of the unified controller operation. The main advantage of the self-designed inverters over commercial ones is that the control system of the inverters is fully accessible to us.

A photographic image of one of the inverters is shown in Fig. 1. The maximum power rating of the inverter is 5 kW. The power stage is realized by the Semikron SKiiP 24NAB126V10 module that contains 7 IGBTs, 6 of which form 3 half-bridge modules, and the 7th one is used for the boost-converter function at the DC-side. Three ISO5852 cards are used as gate drives. The LAUNCHXL-F28379D board with 2-core DSP processor TMS320F2837xD (200 MHz) is used to execute the control algorithms, including PWM, current controller, voltage controller, and/or phase-locked-loop.

The control system for inverters was realized in two different modes: the grid-following mode and the grid-forming one [3]. The flowchart of control systems for the two modes are presented in Fig. 2 and Fig. 3, respectively. Both control modes have the same arrangement of the power stage and the current controller. The grid-following mode also has the phase-locked-loop control block that measures the grid frequency and phase, while the grid-forming mode has the voltage control block instead, which sets the voltage setpoint for the inverter [4].

For both operating modes the power stage control is realized by sinusoidal pulse-width modulation (PWM) [5, 6] with a switching frequency of 20 kHz. Other PWM strategies are also possible, such as third harmonics injection of space vector modulation (SVM), however, they influence only the harmonic content of the inverter current and have minimal effect on the rest of the control systems.

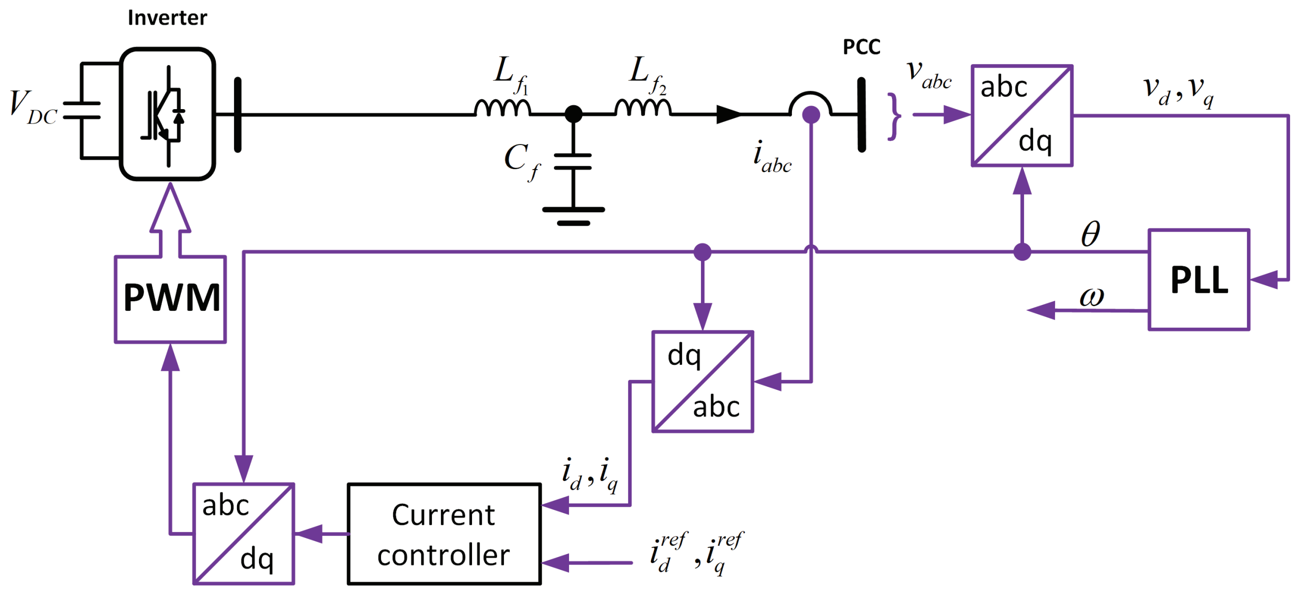

Fig. 2. Flowchart of the inverter control system in the grid-following mode.

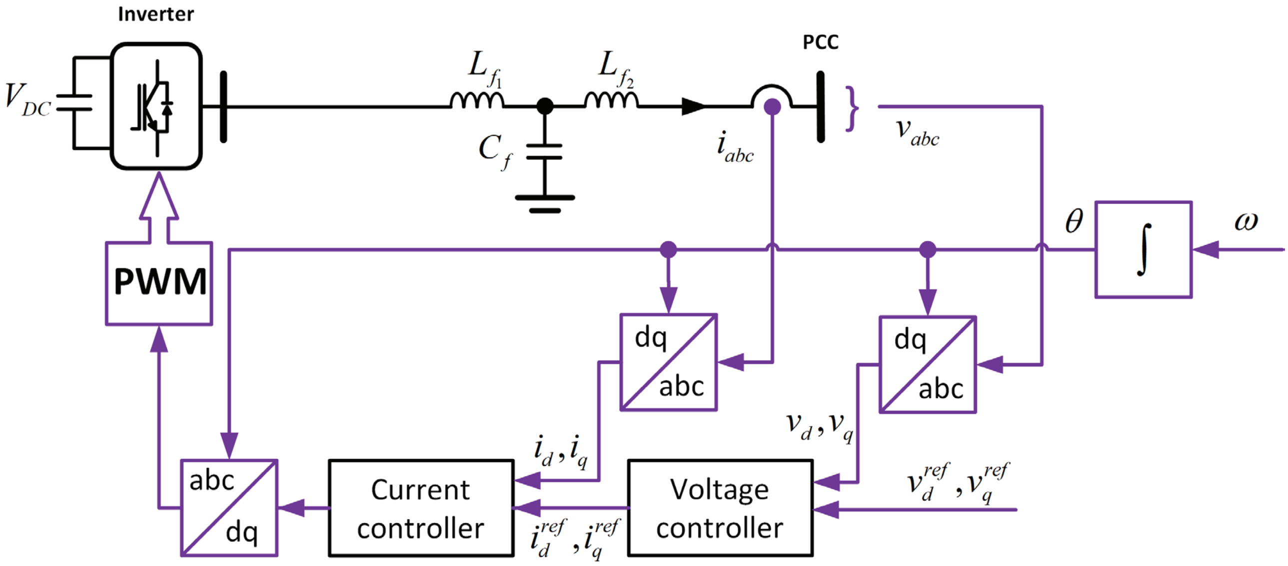

Fig. 3. Flowchart of the inverter control system in the grid-following mode.

The current controller follows a typical $D-Q$ decoupling scheme [3] with a PI controller chosen so as to compensate for the EM-filter dynamics. The bandwidth of the current controller is chosen to be 1 ms. In the grid-following mode of operation, the current controller receives the setpoints for the real and reactive currents i_d^* and i_q^* from the unified prosumer controller. While in the grid-forming mode, the current controller setpoints are received from the voltage control loop of that same inverter.

For the grid-following mode, a phase-locked-loop (PLL) block measures the grid voltage and phase and sends the signals to the current controller and PWM. A standard decoupled double reference frame (DDSRF) PLL is implemented [7] due to its good performance under unbalanced conditions [8]. For the grid-forming mode, the feedback voltage controller [3, 4] is used, for which the voltage reference signal v_d^* and v_q^* is set to be constant. The voltage controller then generates the setpoints i_d^* and i_q^* for the current controller. Both grid-following and grid-forming modes can operate in all 4 quadrants with an arbitrary combination of real and reactive power injection/consumption within the capability curve of the inverter.

III. Validation of controller performance

In this section we present the results of the validation of the unified controller performance by hardware experiments. In order to demonstrate the controller capabilities, a number of controller actions was tested, from simple adjustment of prosumers' setpoints for real and reactive power to a seamless transition of the feeder between islanded and grid-connected operation.

The experimental validation is done using the test bench, described in Part I of the study, which is shown here in more details in Fig. 4. The controller takes high-resolution (20 kHz) measurements from the "ADC" block near the connection to the feeding transformer. Measurements from all the other buses are made at a lower resolution (5–50 Hz). For validation of the controller capabilities, two complex experimental scenarios are realized. Scenario 1 is designed to check the controller ability to update the power setpoints of prosumers following sudden changes in the feeder loading level. Scenario 2 is dedicated to a seamless transition of the feeder between islanded and grid-connected operation. One can view Scenario 1 as testing of "slow" control actions, those taken over a period of several seconds, and Scenario 2 as testing of fast control actions, those taken over a period of several milliseconds. In the latter case, the unified controller's goal is to provide a seamless transition between grid-connected and islanded operation (and back) by quickly reassigning the grid-forming operating mode to one of the inverters once the disconnection from the feeding transformer is detected. The process should be executed in such a way that the load supply is not interrupted.

A. Scenario 1: adjustment of prosumers' power setpoints

In this scenario, we test how the unified controller is able to respond to a sudden load step-change by readjusting the power setpoints of prosumers in such a way so as to keep the (active) power drawn from the feeding transformer constant. Scenario 1 proceeds as follows:

1. The feeder is in the grid-connected mode with no loads initially. Three prosumers are connected to the feeder as shown in Fig. 4. Prosumer 2 operates at the constant power setpoint and is not managed by the unified controller. Prosumers 1 and 3 are initially at the zero-power output (both active and reactive) and managed by the unified controller.
2. An active load of 350 W in each phase is connected at the Load 2 bus, and the unified controller detects the change in the power flow at the input to the feeder.

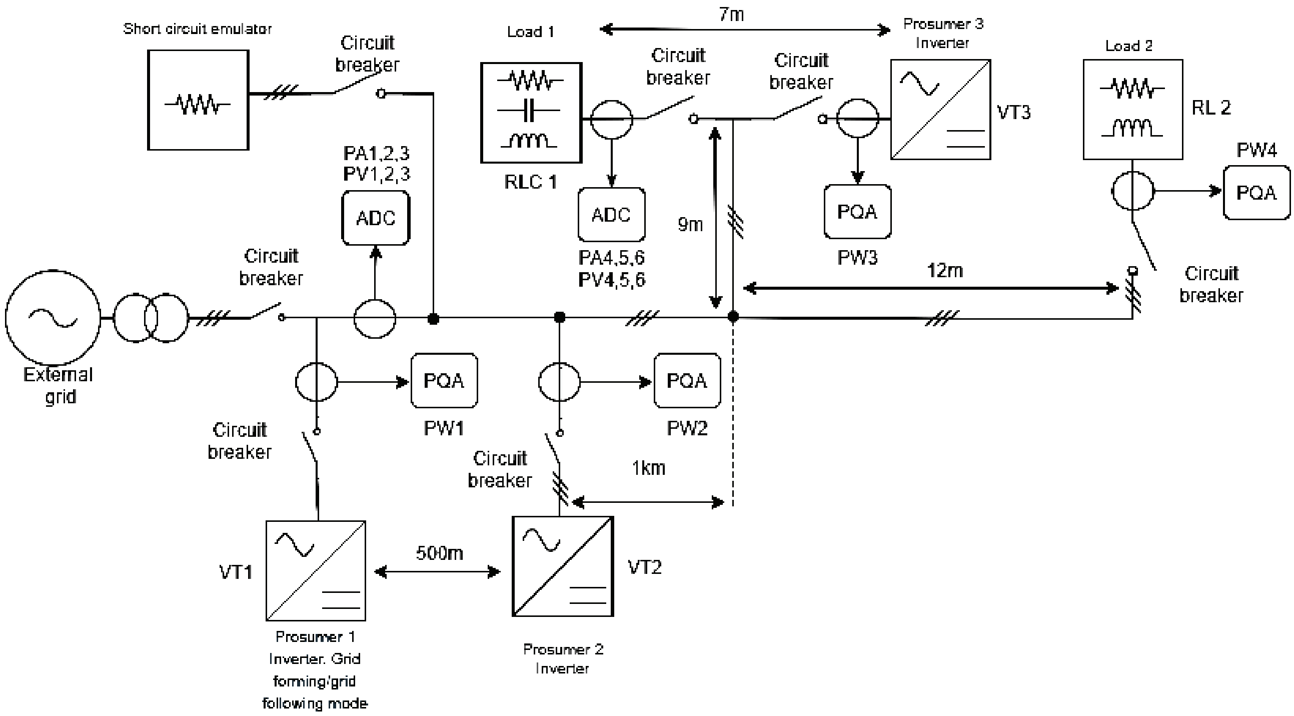

Fig. 4. Single-line diagram of the test bench with loads, prosumers, and the measurement system mounted.

The power setpoints of Prosumers 1 and 3 are then readjusted by the unified controller.

3. After the feeder comes to a new steady-state, a reactive load of 250 VAr in each phase is connected at the Load 2 bus, and the unified controller readjusts the reactive power setpoints of the prosumers in response.

The active powers consumed by the load and drawn from the feeding during the first experiment is shown in Fig. 5. The data is taken from the SCADA system of the test bench. We note that the initial real power drawn by the feeder from the grid is not zero (approximately 200 W), although the loads are not connected to the feeder, which is due to the test bench auxiliary equipment demand. We keep this power constant during the experiments. From Fig. 5 we see that at the moment of time t = 3 905 s a sudden load growth happens (green line) within the next several seconds (load connection is automatically managed by the test bench internal control system, following our manual signal). Likewise, the power drawn from the feeding transformer (orange line) is also increased accordingly during the first seconds. However, after the first few seconds, the unified controller starts to gradually change the prosumers' power setpoints and within about 15 seconds from the initial load step-change the controller is able to restore the active power drawn by the feeder from the grid to its pre-disturbance value. Such a speed of response is more than enough to deal with the possible over-current in the feeder lines and prevent any excessive line heating.

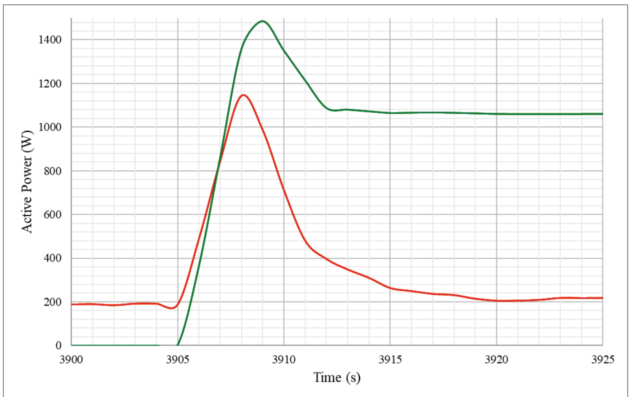

Fig. 5. Change of the active power total load (green) and the active power flow from the feeding substation (orange) after the load increase and subsequent action of the unified controller that changes the power setpoints of prosumers.

More details on how the controller changes the prosumers' active power set-points can be seen at the oscillograms in Fig. 6. Here, the top panel (yellow) shows the feeder voltage and the middle and bottom panels (green and blue) show the currents of prosumers – green stands for Prosumer 3, and blue stands for Prosumer 1. It can be seen that initially, following a load step up, the controller commands both prosumers to increase their power output in order to quickly restore the feeder current back to its pre-disturbance value. However, during the next several seconds the controller is performing a re-distribution of the active power generation between Prosumers 1 and 3 in such a way as to minimize voltage deviation from the rated one on the feeder buses. This leads to Prosumer 3 taking almost all the excessive load and Prosumer 1 restoring its power output to almost the pre-disturbance value (nearly zero).

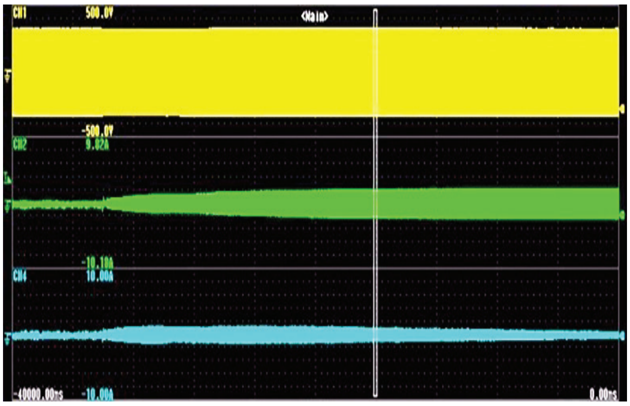

Fig. 6. Oscillograms of the feeder voltage (yellow) and currents of Prosumers 3 (green) and 1 (blue) during the active load increase in the feeder and the consequent unified controller action. It can be seen that the unified controller is compensating for the load increase predominately by increasing the active power setpoint of Prosumer 3.

This is reasonable since the load step change occurred on a bus that is the closest to Prosumer 3, so changing the power output of the closest prosumer induces the least voltage disturbance and the least excessive power flows over the lines in the feeder.

After the transient response to an active load change settles, another disturbance is applied – this time a sudden increase in the reactive load on Load bus 2 (250 VAr for each phase). As in the previous case the controller executes the readjustment of the (reactive) power setpoints of the two prosumers under control. The reactive power drawn from the grid and consumed by the load during the whole process is shown in Fig. 7, which is based on the SCADA system data. As in the previous case, immediately following the sudden increase in the reactive power demand by the load, the reactive power drawn from the grid increases, but then the controller starts to readjust the prosumers' reactive power output, which leads to a change in the reactive power drawn from the feeding transformer within the next several seconds. However, unlike in the case of real power, the reactive power consumption by the feeder is not returned back to the exact pre-disturbance value, but a slight reactive power over-compensation is observed, which is the result of the controller finding the optimal operating point in terms of both power flow and the feeder voltage profile.

Fig. 8 shows oscillograms of the feeder voltage and prosumers' current, where the notation used is the same as for Fig. 6. The process of a reactive power load change starts from the operating point, where the active power output of Prosumer 3 is already substantial (in order to compensate for the previous active load increase) and this can be observed from the middle panel of Fig. 8. In this case, the reactive power setpoint increase is mostly done for Prosumer 3 with little participation of Prosumer 1 even during the transient. Since the increase of the reactive power output of Prosumer 3 is performed already on top of a rather high active power output, it does not lead to a substantial change in the prosumer output current amplitude, so that the oscillogram does not show a very distinct change in the current amplitude.

Overall, the unified controller was able to successfully respond to sudden changes in active and reactive power demands in the feeder and re-adjusted the prosumers' power outputs in order to compensate for the load increase. In both cases of active and reactive power demand increases, the controller drove the total feeder power demand back to

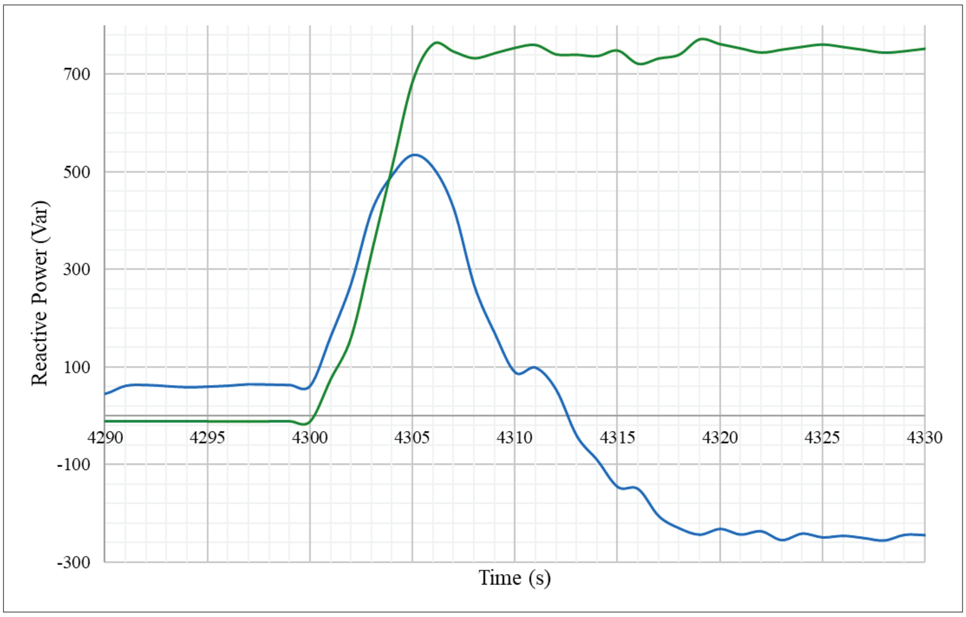

Fig. 7. Change in the active power total load (green) and the active power flow from the feeding substation (orange) after a load increase and subsequent action of the unified controller that changes the power setpoints of prosumers.

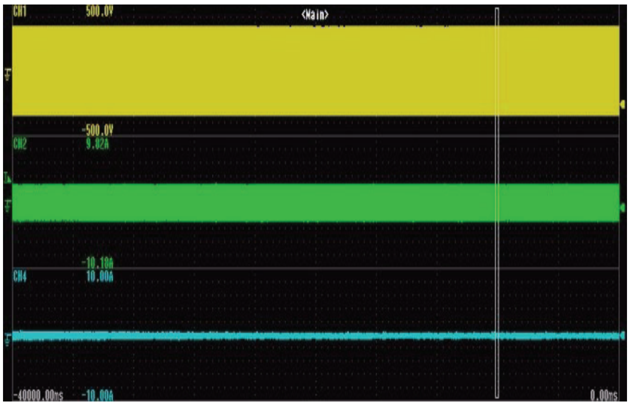

Fig. 8. Oscillograms of the feeder voltage (yellow) and currents of Prosumers 3 (green) and 1 (blue) during a reactive load increase in the feeder and the consequent unified controller action. The excessive reactive power is drawn predominantly from Prosumer 3.

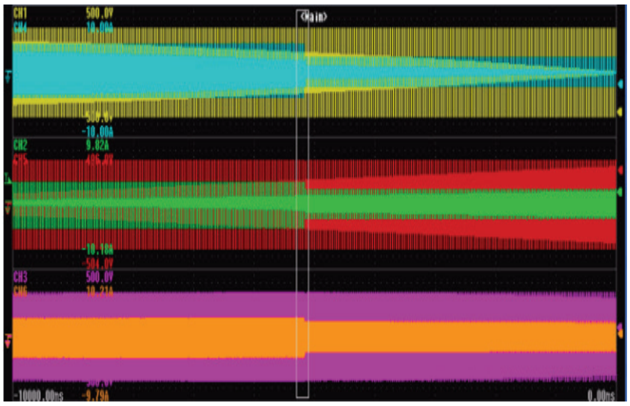

Fig. 9. Transition of the feeder from the grid-connected to islanded operation. Three panels show the voltage and current oscillograms from the three phases of Prosumer 1 inverter that transitions in the grid-forming mode once the islanding is detected.

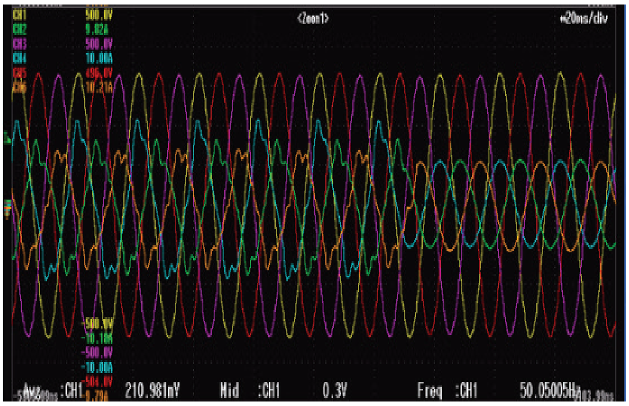

Fig. 10. Detailed oscillograms of the voltage and currents in three phases of the inverter of Prosumer 1 when it goes to islanded operation. The seamless transition is clearly visible for there is no interruption in either current or voltage.

the pre-disturbance values (apart from some slight over-compensation of reactive power) within 10-20 seconds following the load disturbance. This is more than enough to correct any possible violation of the maximum current limits in feeder lines that might happen if the prosumers' control is uncoordinated (or excessive loading occurs). In addition to correcting the power flows, the controller also distributes the real and reactive power loading between the prosumers in such a way as to minimize voltage variations on the feeder buses, so that the prosumer closest to the load disturbance takes the most responsibility. The entire control is implemented in a fully automated way with feedback loops from the measurement system and without any manual intervention (apart from the signals to emulate a load disturbance).

B. Scenario 2: transition from the grid-connected to islanded operation and back

Let us now turn to testing a much more challenging control action: a seamless transition of a feeder under non-zero loading from the grid-connected to islanded operation and back. What is important is that the transition should be done in such a way as to avoid any possible load interruption. For this purpose, at least one of the prosumer inverters should be switched over to the grid-forming mode immediately after the disconnection from the main grid occurs. In our case, this will be Prosumer 1, which can switch between those two modes following the corresponding commands from the unified controller.

In order to test the transition to islanded operation we perform an intentional disconnection of the feeder from the external grid, while the unified controller is in its normal operating state. Once the islanding is detected by the controller, a command is sent to Prosumer 1 to switch its inverter to the grid-forming mode, so that the feeder can continue to operate even without the connection to the external grid. After certain time of the operation in the islanded mode, the reverse transition is initiated by the unified controller commanding Prosumer 1 to switch back to the grid-following mode once the connection to the main grid is detected. Thus, Scenario 2 proceeds as follows:

1. The feeder is in the grid-connected mode with the overall loading of 350 W per phase which is connected at the Load 2 bus. Three prosumers are connected to the feeder as shown in Fig. 4. Prosumer 2 operates at the constant power setpoint (equal to zero) and is not managed by the unified controller. Prosumers 1 and 3 are initially at the zero-power output (both active and reactive) and managed by the unified controller.
2. While the unified controller is in the normal operating state, the feeder is suddenly disconnected from the external grid by tripping of the corresponding circuit breaker. The controller automatically detects the islanding event and sends the corresponding command to Prosumer 1 for switching to the grid-forming mode. An additional command is sent to Prosumer 3 to change its active power output.
3. Prosumer 1 switches to the grid-forming mode, while Prosumer 3 also adjusts its power output, so that the load is fed without any interruption.

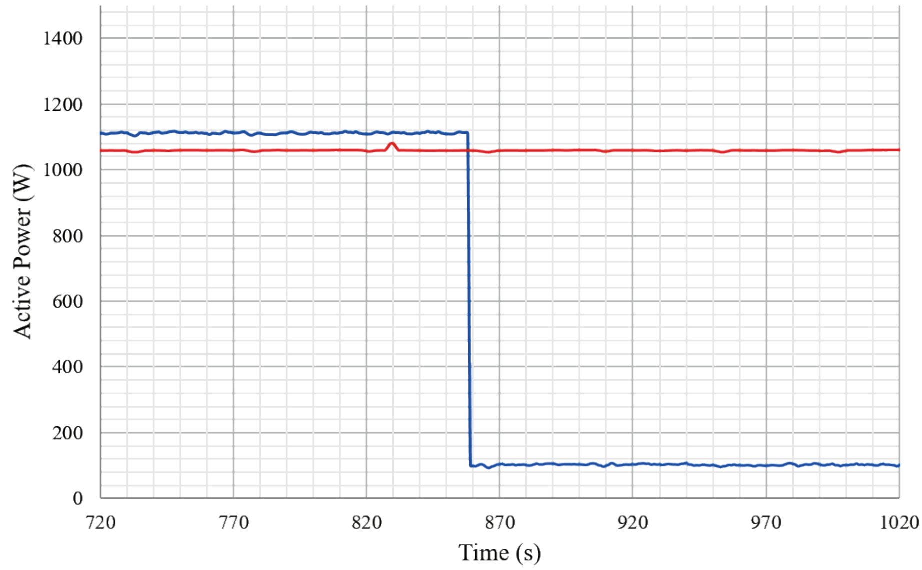

Fig. 11. Active power supplied to the load (orange curve) and consumed from the grid (blue curve) during the process of transition between grid-connected and islanded operation.

4. After some time of the islanded operation (about 5 minutes) the external grid voltage is back, and the feeder can be reconnected. Upon observing the normal grid voltage, the controller sends the corresponding signals to Prosumer 1 operating in the grid-forming mode in order to adjust the frequency and phase so that a seamless reconnection can take place.
5. The reconnection to the external grid occurs with Prosumer 1 switching back to the grid-following mode with the constant power output (the same as before the islanding). At the same time, the power setpoint of Prosumer 3 is also returned back to the value before the islanding. The load is fully served without any interruption during the entire experiment.

Fig. ***9*** shows the oscillograms of the three phases of the inverter of Prosumer 1 during the process of islanding. It is clear that the transition occurs with a change in the inverter current. Fig. ***10*** shows the actual transition process to the islanding mode in more detail. Here, the oscillograms of voltages and currents in all three phases of the inverter are shown. The transition is clearly visible, and its seamless character can be also seen – there is no discontinuity of any kind in currents in any phase. The inverter currents are slightly distorted by harmonics while in the grid-following mode, but this is the result of some flaws in inverter internal controls and neither affects the unified controller performance nor the transition between grid-following and grid-forming modes.

Fig. ***11*** shows the active power supplied to the load (orange curve) and consumed from the grid (blue curve) during the process of islanding. It is clearly visible that the power drawn from the grid goes to zero (apart from the

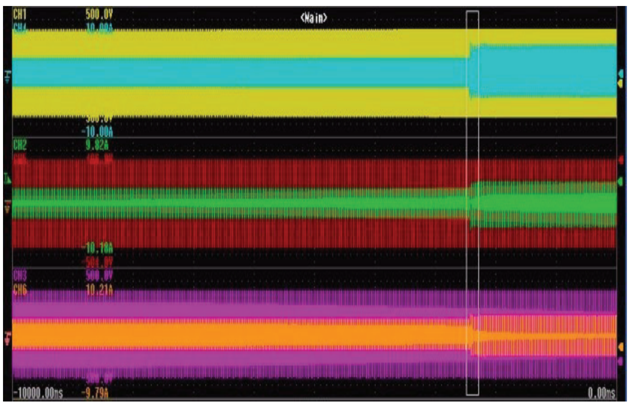

Fig. 12. Transition of the feeder from islanded to grid-connected operation. Three panels show the voltage and current oscillograms from the three phases of the Prosumer 1 inverter that transitions in the grid-following mode once the connection to the external grid is detected.

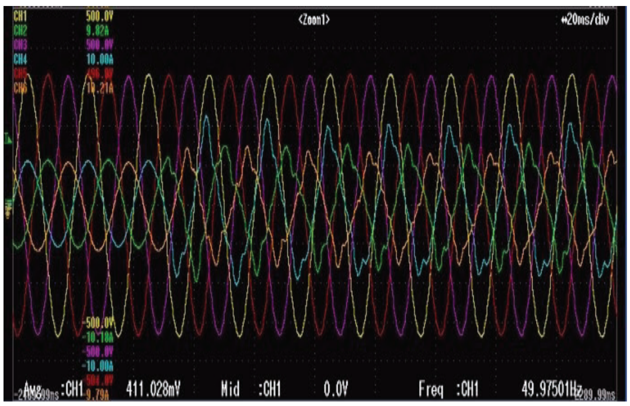

Fig. 13. Detailed oscillograms of the voltage and currents in three phases of the Prosumer 1 inverter 1 when it transitions from islanded to grid-connected operation. The seamless transition is clearly visible for there is no interruption in either current or voltage.

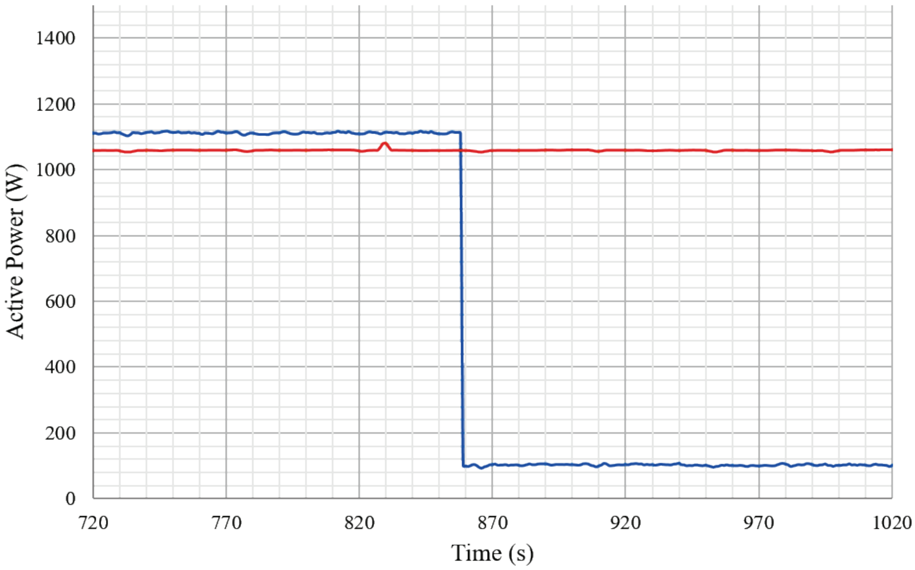

Fig. 14. Active power supplied to the load (orange curve) and consumed from the grid (blue curve) during the process of the transition between islanded and grid-connected operation.

demand on the part of the test bench auxiliary equipment) after the feeder disconnection is performed. However, the load is supplied in an uninterrupted way during the whole process which is guaranteed by the action of the unified controller that has performed the transition of the feeder to islanded operation.

After some time operating in the islanded mode (around 5 minutes) we perform the reconnection of the feeder back to the main grid, with the controller taking care of the seamless transition. Fig. ***12*** shows the oscillograms for the three phases of the inverter of Prosumer 1 during the process of the transition from islanded to grid-connected operation. It is also visible, as in the previous case, that the transition is followed by a change in the inverter RMS current. Fig. ***13*** shows the actual transition process from islanded to grid-connected operation in more detail, where the oscillograms of voltages and currents in all three phases of the inverter are shown. The transition is clearly visible and its seamless nature can be also seen: there is no discontinuity of any kind in currents in any phase.

Finally, Fig. ***14*** shows the active power supplied to the load (orange curve) and consumed from the grid (blue curve) during the process of switching from islanded to grid-connected operation. We see that the power drawn from the grid goes from zero (apart from the demand on the part of the test bench auxiliary equipment) to the load value after the re-connection to the grid is completed. As with the process of islanding, the load is supplied in an uninterrupted way during the whole process which is guaranteed by the action of the unified controller that has performed the transition of the feeder back to grid-connected operation by sending control commands to Prosumer 1 inverter to switch to the grid-following mode, once the re-connection happens.

IV. Conclusion

With power electronics devices becoming more widely available and with the reduction of prices for energy storage and renewable power sources, traditional distribution will undergo significant changes, where conventional consumers will turn into prosumers, grid participants that can both consume and produce power. It is only a matter of time when the wide spread of prosumers and their uncoordinated control will lead to exacerbating the issues of grid security and stability. Thus, there is a need for development of methods for coordinated prosumer control that can be realized in distribution grids. This control can become challenging due to complex dynamics of power electronics devices, so research is needed in order to develop control algorithms and ways of their implementation.

In this two-part study we have presented the unified controller for prosumers connected to 0.4 kV distribution grids. We have described the controller architecture and basic functions, and then performed extensive testing of the controller performance using a laboratory test bench. Our controller has a broad range of possible control actions that it can execute, ranging from rather simple adjustments of power setpoints to seamless transitions between inverter operating modes. Our experimental validation represents a first step towards the commercial-scale controller implementation.

Further research and development can be focused on the design of controllers with different requirement with respect to communications and computational infrastructure. For such applications as power setpoints adjustment possible simplifications can be made, and requirements for sensors and controller performance can be relaxed. Another direction is the possible coordinated control of prosumers connected to different (but adjacent) feeders, which can be realized by some coordinated action of multiple unified controllers acting on different feeders.

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Integration of Components of the Ontological Knowledge Space to Assess the Impact of Energy on Quality of Life of the Population

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***Abstract* — This paper examines an ontological approach to integrating knowledge to support interdisciplinary studies in energy and ecology in terms of quality of life assessment. These studies involve the integration of environmental and social components. The environmental component is determined by natural and climatic conditions and the state of elements of the natural environment of a particular territory. The social component implies meeting the electricity and heat demand of the population, which is necessary for comfortable living. Quality-of-life metrics are considered as a way to assess the positive and negative impacts of the energy facilities and population on the natural environment to compare these impacts. We present ontologies detailing basic concepts of the subject area of research into the impact of energy facilities and quality of life and reflecting their integration into a single ontological space of knowledge. The ontological approach provides a visual representation and integration of knowledge from different subject areas.**

***Index Terms*: Ontological approach, anthropogenic impact, quality of life, energy, environment, ecology.**

I. Introduction

The studies of the anthropogenic impact of energy facilities on the environment and humans are conducted at the Melentiev Energy Systems Institute SB RAS within the framework of the project supported by RFBR grant № 20-07-00195 "Methods for constructing an ontological knowledge space for intelligent decision-making support in energy and ecology, taking into account the quality of life." These studies rely on semantic methods (in particular, ontological and cognitive modeling) that represent the elements of such intelligent support. The ontological knowledge space for research includes a set of interrelated ontologies developed to ensure the consistency of terminology of subject domains, the integration of overlapping areas of knowledge, and their structuring [1]. Research and assessment of the anthropogenic impact of the energy sector on the natural environment and quality of life of the population require knowledge primarily in the subject domains of energy and ecology. The "Quality of life" concept is employed to factor in the requirements for the operation of energy facilities related to the living conditions of the population and the need to preserve the natural environment for present and future generations.

II. Literature review

The problem of assessing the impact of energy facilities on the environment and quality of life is of importance due to the transition to environmentally friendly and resource-saving energy. Scientists are considering various aspects of the negative consequences of the functioning of energy enterprises for nature. For example, the studies presented in [2-6] focus on the environmental impact of the energy industry. In [3], methodological features of the risk assessment for the population health under the influence of chemicals that pollute the environment are analyzed. The authors of [4] make a comparative analysis of the pollution of landscapes adjacent to a high-capacity thermal power plant. The study presented in [6] is devoted to collecting, structuring, and searching for environmental data using a decision support system and knowledge management based on ontologies.

Semantic technologies and ontologies used for data modeling are proposed in [7, 8]. The book [9] is a comprehensive source of scientific information on the latest research on sustainable development from an interdisciplinary point of view. It offers an overview of innovative topics such as renewable energies, urban development, and green technologies.

III. Environmental and social components of research into the anthropogenic impact of energy

The environmental impact of the energy industry is one of the most serious ones as it manifests itself in all stages of

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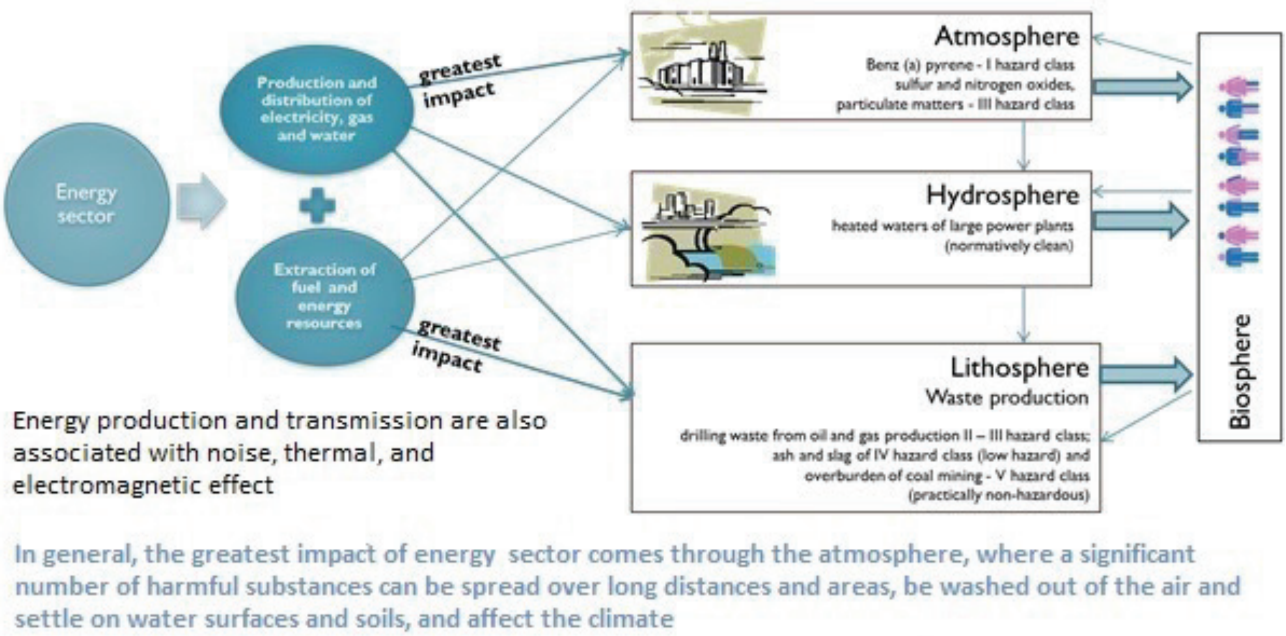

Fig. 1. Diagram of the environmental impact of the energy industry.

energy production and leads to pollution of all elements of the natural environment: the atmosphere, water bodies, and soil (direct impact) (Fig. 1). In addition, there is an indirect effect on vegetation, wildlife, and humans.

Extraction of energy resources has the most sizeable direct impact on soils and water bodies. It is related to the withdrawal of large areas during oil, natural gas, and coal extraction, especially by open-pit mining, and storage of tailings and sludge waste. Untreated storm and sludge water resulting from extraction usually enters water bodies. Fuel conversion into electricity and/or heat is characterized by the most considerable impact on the air basin (atmosphere) and soils. Pollutants of hazard classes I, III, and IV are released into the atmosphere, and ash and slag waste from coal combustion are deposited in significant quantities on the soil. The transport of energy resources in each stage, from fuel extraction to electricity and heat delivery to the consumer, has a direct impact on each element of the environment.

Previous studies provided a detailed description and presented the ontology of the concept of "anthropogenic factor," the properties of which depend on the energy facility type, fuel, and technology of its combustion [10]. For a more detailed study of the anthropogenic impact of energy facilities on the elements of the natural environment, it is proposed to systematize the interrelated concepts of "anthropogenic impact," "anthropogenic pollution," and "anthropogenic consequence," which are defined as follows:

- an anthropogenic impact is the consequence of an anthropogenic factor, the process of influence of economic or other human activity on elements of the natural environment;
- anthropogenic pollution is the result of changes in elements of the natural environment caused by an anthropogenic impact;

Table 1. Composition and properties of pollutants from energy facilities.

Element of the natural environment	Pollutant	Hazard class	Type of exposure							
			C	B	C	T	A	L	S	Other
Atmosphere	inorganic dust	III	+							
Soils			+							physical
Atmosphere	benzo(a)pyrene	I	+	+	+	+	+	+	+	
	soot	III	+	+			+		+	
Atmosphere	sulfur dioxide	III	+	+		+	+	+	+	
Bodies of water	nitrogen oxides	III	+	+		+	+		+	photochemical
Atmosphere	carbon dioxide	IV	+	+						greenhouse effect
Bodies of water	petroleum products	III	+	+		+	+	+		
	Thermally enriched water	-	+							thermal
Soils	ash and slag waste	IV	+	+						physical aesthetic

Note: C - chemical, B - biological, C - carcinogen, T - toxicant, A - bioaccumulative, L - long-lived, S - synergistic

- an anthropogenic consequence is the result of anthropogenic pollution, characterizing the degree of change in elements of the natural environment.

Such detailing makes it possible to classify the types, properties, and a quantitative measure of these concepts following available methodological approaches to assess anthropogenic impacts.

These comprehensive studies imply the integration of environmental and social components in assessing the impact of the energy industry on the quality of life of the population.

The environmental component of the research is determined by the state of natural environment elements in a particular territory exposed to the anthropogenic impact and by the natural and climatic characteristics of this territory. We have analyzed the composition of pollutants from energy facilities entering various elements of the natural environment, see Table 1.

The anthropogenic impact is determined by anthropogenic burden, which depends on the composition of pollutants, their hazard class, and physical and chemical properties. In addition, the level of the anthropogenic burden is influenced by climatic, orographic, and background conditions of the territory that pollutants enter.

Hazard class is a harmful effect value intended for simplified classification of potentially hazardous substances. Attributes used to determine the class of danger are specified by a dedicated standard [11]. According to the relevant State Standard (GOST), a harmful substance is a substance, which, when in contact with the human body in case of violation of safety requirements, can cause occupational injuries, occupational diseases, or health deviations detectable by modern methods both in the work process and during the life of present and future generations in the long run [12]. For example, the main human diseases caused by air pollutants from coal-fired power facilities are shown in Table 2.

The social component is considered in two aspects. First, it implies meeting the needs of the population for electricity and heat, which are necessary for comfortable living. Second, the functioning of energy facilities should not adversely affect the health of the people living in the corresponding territory.

These aspects are significant parameters of quality of life [13]. In some countries, researchers consider the concept of "quality of life" as a set of objective and subjective parameters that characterize different aspects of human life, the satisfaction of a person with their position in society, financial and social well-being, health, and others [14-16]. Commonly, quality of life is characterized by indicators related to health care, education, demography, economic conditions, environmental conditions, living conditions, employment, and the ability to exercise constitutional rights [17-19].

IV. The Structure Of The Ontological Space Of Knowledge

The main components of the ontological space of knowledge for research are ontologies reflecting the relationships between some areas of energy, ecology, and quality of life. The structure of the ontological knowledge space relies on the fractal approach, which assumes the presence of meta-levels for each area and their further stratification and detailing at each subsequent level [20].

Meta-ontologies contain descriptions of the basic concepts of the respective subject areas relevant to collaborative research. Such basic concepts are "Energy," "Ecology," and "Quality of Life." Ontologies detailing the description of the research sections at the lower levels are the description of facilities, resources, production processes in the case of the energy section; the description of elements of the natural environment, anthropogenic factors in the case of the ecology section; and the description of influencing factors and metrics of quality of life. The linking elements of these sections of the ontological space are the basic concepts of the "anthropogenic factor" induced by energy facilities and the "element of the natural environment," which is affected by the anthropogenic factor and influences the quality of life. The basic concepts of the meta-ontology are as follows:

Energy is the field of economy, science, and technology covering energy resources and production, transmission, conversion, accumulation, distribution, and consumption of various energy types [21].

Ecology is a branch of biology, a cross-disciplinary science studying the habitat of living beings and their interaction [22], including the structure and functioning of supra-organismal systems (populations, communities, ecosystems) in space and time under natural and human-altered conditions. This definition reflects, to a greater

Table 2. The main diseases from pollutants in the atmosphere.

Pollutants	Diseases			
	Respiratory tract	Eyes	Cardiovascular system	Oncological
Benzo(a)pyrene	+	+	+	+
Soot	+	+	+	+
Inorganic dust	+	+	+	-
Sulfur dioxide	+	+	+	-
Carbon monoxide (with prolonged exposure)	+	+	+	-
Nitrogen oxides	+	-	+	rarely
Carbon dioxide	+	-	+	-

Energy resource
- Type (coal, gas, oil)
- Property (renewable, non-renewable, calorie content)

Energy object
- Type (nuclear, hydroelectric, thermal power plants)
- Property (power, fuel consumption, incineration method, degree of capture)

Anthropogenic factor
- Type (waste, release, discharge, noise, radiation)
- Property (mass of waste, release, discharge, periodicity, state, migration)

Anthropogenic impact
- Type (physical, chemical, mechanical, biological, thermal, light)
- Property (frequency, duration, anthropogenic load)

Anthropogenic pollution
- Type (biological, chemical, physical)
- Property (accumulation, synergy, durability, pollution level)

Anthropogenic consequence
- Type (acidification, disturbance, destruction, formation, alteration, depletion)
- Property (reversibility, accumulation, exceeding the limit, degree of change)

Element of the natural environment
- Type (atmosphere, waterbody, soil, living organism)
- Property (renewable, non-renewable, calorie content)

Energy object creates *Anthropogenic factor*
Energy object uses *Energy resource*
Anthropogenic factor implements *Anthropogenic impact*
The anthropogenic impact creates *Anthropogenic pollution*
Anthropogenic pollution forms *Anthropogenic consequence*
Anthropogenic consequence manifests itself in *Element of the natural environment*
Energy resource is related to *Element of the natural environment*

Fig.2. Ontology of anthropogenic impact of energy facilities on elements of the natural environment.

extent, the current trend to study the consequences of industrial and other human activities for the environment.

Quality of life is an overall characteristic of the level of objective and subjective living conditions of the population, which determine physical, mental, and socio-cultural development of a person, group, or community of people [23]

The anthropogenic factor is the cause of anthropogenic impact on the natural environment, which is due to the process and operating conditions of the facility, its characteristic features [24].

The natural environment is a set of environmental factors that affect people, including natural factors and those slightly modified by human activities. It has the feature of self-sustaining and self-regulation without human corrective action [22].

V. Components of the ontological space of knowledge

An earlier research [10] presented a meta-ontology of concepts related to the impact of energy on the natural environment, including those of energy facility, energy resource, element of the natural environment, as well as an anthropogenic factor, anthropogenic impact, anthropogenic pollution, and anthropogenic consequence. As a result of their more detailed consideration in line with the rules of ontological engineering, it is proposed to systematize the characteristics of these basic concepts by their type and property (Fig. 2).

These characteristics make it possible to establish relationships between the basic concepts of the meta-ontology. In particular, the type of energy facility is related, on the one hand, to an energy resource type used and, on the other hand, affects the type of anthropogenic factor generated. The type and mass of waste, emissions, and discharges produced depend on the properties of energy facilities that describe their technical and technological features (method of combustion or degree of treatment) and the quantitative measure (power, fuel consumption). The type of anthropogenic impact, the nature, and the magnitude of the anthropogenic burden depend on the type of the anthropogenic factor and its quantitative measure. Further, the type and level of anthropogenic pollution depend on the type of the anthropogenic impact (physical, chemical, and others) and its properties (duration or periodicity). In turn, the level of anthropogenic pollution, its type, and properties affect the type, properties, and quantitative measure of the resulting consequences of the anthropogenic impact of energy facilities on elements of the natural environment.

The presented ontology fragment does not fully reflect all the complex relationships between the concepts under consideration. For a more detailed assessment of the anthropogenic impact of an energy facility within a specific territory, one should consider the relationships between the characteristics of this facility and corresponding characteristics of all other components of the presented ontology at the next level of the ontological knowledge space. The proposed ontology reflects the structure of knowledge required to assess the ecological component of research.

VI. Energy and quality of life of the population

To compare the positive and negative impacts of energy facilities on the population and the natural environment, quality of life metrics are considered as a means to assess these impacts. Quality of life is an interdisciplinary concept that captures multiple aspects of human activity. Research on quality of life is conducted by scholars in many countries, although there is no unambiguous definition of this concept. According to the World Health Organization, it includes the physical, social, and cultural development level and is characterized by the indicators related to health, education, economic conditions, environmental conditions, living conditions, and others [25]. The indicators for assessing the quality of life depend on the research field. In economics, the emphasis is on the extent to which basic material human needs are met, the level of human development, the degree of security, and others. Sociology explores cultural needs, access to education, quality of service, and the like. Medicine requires the evaluation of the quality of health care services and health parameters. The level of pollution and related consequences, which characterize the quality of elements of the natural environment, is of utmost importance for the ecology.

There are many techniques for assessing the quality of life, such as the calculation of metrics, sociological surveys, statistics on social phenomena, and others [26]. The main indicators of quality of life in different countries depend largely on the stage of their economic development. The central metric of quality of life is the Human Development Index (HDI) designed by the participants of the UN development program, which includes the following basic parameters: life expectancy, level of education, and gross domestic product (GDP) per capita. Objective and subjective metrics are considered to assess the quality of life. Objective metrics reflect natural and social aspects of life, such as the level of well-being and development of social infrastructure, the quality of elements of the natural environment, and natural conditions. Subjective metrics include cognitive and emotional assessments of a person's life satisfaction (working and leisure conditions, safety, confidence in the future). A comprehensive assessment relies on integrated indicators, which cover such components as welfare (income, housing, infrastructure), social sphere (working conditions, safety), quality of the population (family, education, qualifications, demography), quality of elements of the natural environment (air, water, soil, biological diversity), and natural conditions (climate, natural resources, circumstances of insuperable force).

We propose the following meta-ontology of knowledge to compare the positive and negative effects of energy facilities on the quality of life of the population (Fig. 3).

Fig. 3. Meta-ontology of basic metrics of quality of life

This structure of the components of the ontological space of knowledge reflects the basic concepts related to the quality of life and its main indicators. The heat and electricity generation, in particular, on the one hand, directly affects the economic development of the territory and quality of life through the improvement of living conditions and social infrastructure. Indirectly, there is a positive impact on living standards, provision of leisure and recreation through the economic development of the territory. On the other hand, the impact of energy on elements of the natural environment negatively affects health and safety, thereby compromising the quality of life. The presented scheme reflects the basic components of the ontological space of knowledge related to the ongoing research on the impact of energy on the quality of life.

VII. Conclusion

These studies are a continuation of work on building the ontological space of knowledge to integrate it for interdisciplinary energy-ecology research in terms of assessing the quality of life of the population. This paper presents a group of ontologies related to the concept of the anthropogenic impact of energy facilities on elements of the natural environment. The anthropogenic impact is determined by its anthropogenic burden, which depends on the composition of pollutants, their hazard class, physical and chemical properties, and on the climatic, orographic, and background conditions of the territory. These studies require integrating the environmental and social components to compare the positive and negative effects of energy facilities on the population and the environment. We propose treating the indicators of quality of life as a means to assess these effects. The performed ontological engineering of the intersection of knowledge of different subject domains and the proposed ontological models provide a visual representation and structuring of the interrelated components of the knowledge.

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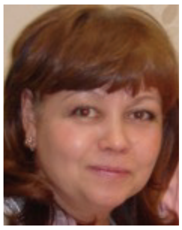

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Key Aspects of the Seventh Energy Transition And Its Point of Divergence and Mutually Acceptable International Economic Solutions For Russia

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***Abstract* — In this author's view, current energy transition is the seventh one in human's history. But it is the first one triggered from the demand-side by climatic considerations aimed at decrease of GHG emissions to reach their net-zero level. And it will not end up with another one dominant energy, as in the past, but with competitive energy mix of both renewable and non-renewable energies based on economic, ecologic & climatic considerations. EU decarbonisation is based on "renewable electricity plus decarbonized gases" political concept. Renewable hydrogen is politically predetermined choice in the EU (though within the distorted frame of reference, as this author proves) and hydrogen from natural gas is given only temporary future in the EU. But EU will not manage to produce all hydrogen needed domestically and looks for its import from neighboring states, including Russia. Two concepts of how to organize Russia-EU hydrogen cooperation are debated. EU/German concept is to produce green and blue hydrogen in Russia and to export it to the EU. This means through the existing Russia-EU gas transportation system which will predetermine its costly deep modernization up to full reconstruction/replacement. The author proves why this concept is counterproductive for Russia. He proposes alternative concept: to continue with natural gas supplies from Russia to the EU and to produce hydrogen in the "hydrogen valleys" inside the EU: in continental Europe - by pyrolysis (without CO_2 emissions), and in the coastal areas of North-West Europe – also by methane steam reforming with CO_2 capture and sequestration in the depleted fields in the North Sea.**

***Index Terms*: *renewable energy sources, hydrogen energy, renewable hydrogen, energy transition, hydrogen international cooperation, European Union, Russia, technological neutrality*.**

Highlights

- Not the first or fourth but the seventh energy transition;
- Economic vs climate competition between non-renewable and renewable energies;
- Renewable hydrogen (water electrolysis with renewable electricity) vs non-renewable hydrogen (methane pyrolysis without direct CO2 emissions and/or methane steam reforming with CO2 capture and sequestration) vs technological neutrality principle in the EU;
- Renewable hydrogen in the EU vs three Scopes of GHG emissions;
- The EU-Germany concept of hydrogen cooperation with Russia and controversial Russia's position on hydrogen export;
- The alternative win-win concept based on Russian natural gas supplies to the EU and hydrogen production inside the EU by pyrolysis and methane steam reforming with CO2 capture and sequestration.

I. Introduction

Today, the main publicly discussed topics in the international energy industry are, perhaps, various aspects of the current "energy transition" or "green revolution", that is, a change in the social and technological order and the basic paradigm of the world energy development towards reducing the negative impact on the environment, primarily by reducing greenhouse gas emissions and thereby curbing global warming and its negative consequences. Already at this point, there are very significant differences of opinions, beginning with which energy transition is the current one.

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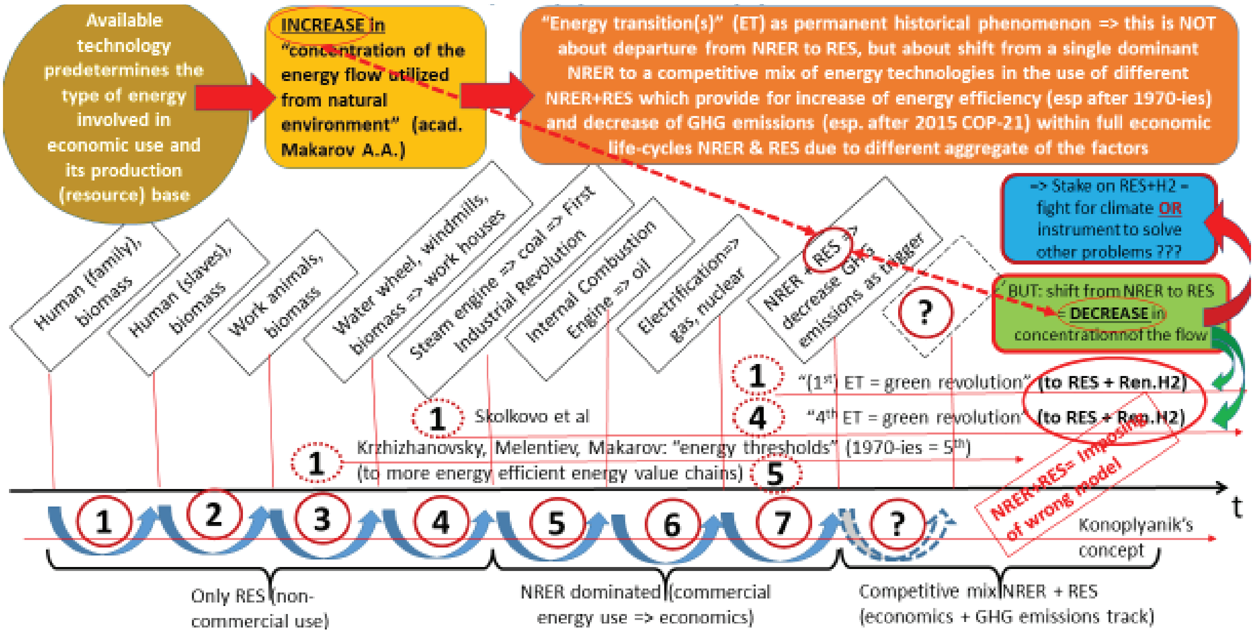


Fig. 1. "Energy Transition(s)" (ET): duration of considered historical time period does matter (Konoplyanik's concept).

II. Which energy transition: the first or the seventh?

In the narrowest sense, the term "energy transition" is interpreted by a number of authors as a phenomenon of modern history only. It is believed that the German term "Energiewende," which can be translated as "energy transition," "energy turn," "energy revolution," in the sense of changing the entire global energy industry, first appeared in 1980 as the title of a publication by the German Öko-Institut [1] and became widely used in Germany in the early 2010s [2]. S. Griffits notes that "although the term 'energy transition' has no single meaning, it usually means the gradual replacement of the use of fossil fuels by renewable energy sources" (RES) [3]. Some authors were quick to call such comments about increasing the share of renewables in the global energy balance "the theory of the global energy transition" [4].

There is also a broader dimension available to the energy transition in the modern world – the transition from one dominant non-renewable energy resource (NRER) to another, and then the transition from NRER dominance to RES dominance. Adopting this approach, some researchers suggest that the current energy transition is the fourth one, "from biomass (firewood) to coal, then to oil, then to gas, and now to renewables" [5]; others, with a similar approach, think of it as only the third one (apparently: coal, hydrocarbons, renewables), also considering only the "modern history of industrial and technological development," while talking about "the transition to a new 'electric world" [6].

In this author's broader understanding, the "energy transition" is a progressive shift in social development from one technological order to another, in which one or another energy resource dominates (as it did in the past) or a competitive (without an obvious dominant energy resource) energy consumption structure is formed (as it is happening now and, in the author's opinion, will happen in the future), throughout the development of human civilization, not only from the beginning of industrialization period to the present. In this author's opinion, the basis of this or that "technological order" (the term coined by D.S. Lvov and S.Yu. Glazyev [7]) is the overcoming of the corresponding "energy threshold" (if we follow the terminology of Academician G.M. Krzhizhanovsky [8]), that is the transition to a qualitatively new level of energy consumption, not so much with respect to the volume of energy consumption, as by its qualitative structure.

If one is to follow the conceptual vision advocated by Acad. G.M. Krzhizhanovsky, L.A. Melentiev, and A.A. Makarov, then the authors refer to the first "energy threshold" as that of the creation of the water wheel (and then the use of wind energy in mobile and stationary energy as well), which effectively replaced human and animal muscle power, and then the transition to the use of coal (along with firewood) after the appearance of the Watt steam engine. According to L.A. Melentiev's view as of mid-1970-ies, "currently developed market economies are placed within conditions characteristic for the fifth energy threshold which is finalization of forming united energy systems, which they have approached to approximately within 1950-ies/1960-ies" [9]. He also considered that the then "USSR in the last quarter of the XXth century has been slowly approaching the sixth energy threshold" [10].

However, if we look even more broadly, energy transitions did not begin with the first industrial revolution or with the preceding use of the water wheel (the time of development of workhouses) and wind power in pre-industrial time, but much earlier – with the primitive-communal system, when the struggle began for access to material and energy resources and/or for their mastery through various engineering tricks, the achievements of scientific and technological progress (STP) (see Fig. 1).

The first energy resources to provide a minimum level of consumption by human beings (their families) within the framework of simple reproduction were renewable energy sources – the muscle power of human beings themselves and their family members and biomass/wood (after mastering fire). If we count back from this time, then the first energy transition, in this author's opinion, was the expansion of the use of human's physical strength through the additional use of the physical strength of other people – prisoners of war being converted into slaves. This happened in the transition to expanded reproductive performance. That is, the energy resource remained the same (human muscle power), but its source changed: not only the expansion of energy sources within the family by means of fertility and family bonds but also from outside the family by means of slave labor (there was, in fact, the first diversification of energy sources, though not on a commercial basis since the muscle power of slaves was not purchased but conquered).

The second energy transition is the involvement in the energy balance of the muscle power of tame and thus becoming domesticated work animals (draught cattle).

The third is the expansion of the use of RES (wind and water energy) after the invention of wind and water mills (the beginning of the "energy thresholds" of Acad. G.M. Krzhizhanovsky). The use of the latter ensured the development of textile factories (work houses) and was the forerunner of the First Industrial Revolution. However, these RES were mainly suitable only for stationary use along with the use of wind energy in mobile energy by the sailing fleet. And it was only the steam engine that gave rise to the development of mobile energy (at sea and on land) and the coal industry as a source of fuel for steam plants (in stationary and/or mobile applications).

Thus, in this author's frame of reference, the transition to coal is the fourth energy transition (rather than the first one [5, 6]), and the current one, therefore, is the seventh one (rather than the fourth if we divide the period of hydrocarbon dominance into separate periods of oil and gas dominance, as in [5], or the third if we merge them, as, apparently, is done in [6]).

This provides few valid additional arguments to the debate on the substance of energy transition. Those who began the count from the First Industrial Revolution and thus trying to prove the shift from NRER to RES as the very substance of "energy transition" further to their interpretations of the previous historical trends, just either forgot (or intentionally exclude) the previous "energy transition" from pre-industrial to industrial time which was a transition from RES to NRER (see Fig. 1). And that was a reverse process to the imposed vision of the current energy transition as if from NRER to RES. All previous energy transitions were characterized, according to academician A.A. Makarov, by clear and definite trend: "consequent passing through the energy thresholds was accompanied by increasing concentration of the energy flow utilized from natural environment" [11], including through the involvement of NRER of higher and higher quality (first coal, then oil, then natural gas). The imposed shift from NRER to RES as if current "energy transition" leads to decrease of the above mentioned "concentration of the energy flow utilized from natural environment".

This is why I do consider "energy transitions" as permanent historical phenomenon which is NOT about departure from NRER to RES today or in the longer trend, but it is nowadays about shift from a single dominant NRER to a competitive mix of energy technologies in the use of different NRER+RES which provide for increase of energy efficiency (especially after the 1970-ies) and decrease of GHG emissions (especially after 2015 COP-21) within full economic life-cycles NRER & RES due to different aggregate of the factors. And it is not energy resource per se that does matter, but it is available technology which predetermines the type of energy involved in economic use (now both energy and climate efficient) and its production (resource) base.

All previous energy transitions were determined by the introduction of new energy sources into the energy balance due to the achievements of the revolutionary STP, and mainly on the supply side. In contrast, the current energy transition is caused by man-made restrictions on demand for primary and final energy in connection with the climate agenda. Therefore, it is accompanied by containment and even contraction of supply of NRER that have been dominant to date and maintain its dominant position in their "conventional version", that is, without restrictions on emissions.

In Russia, the questions of what place this country should take in the current energy transition and how to build international cooperation in it, primarily with Europe as our main export market, are certainly added to this discussion with much practical consequences.

III. NRER and RES: economic vs. climate competition, before and after the Paris Agreement

For the EU, the severity of the climate problem is obvious and is largely the result of the industrial model of development. Industrialization began earlier in the Old World than in other parts of the globe, so it is there that its negative effects, in particular the growth of greenhouse gas emissions from energy, industry, and transport, have first manifested themselves. The climate agenda is often given exaggerated importance, which means that it is given such an excessive attention that it can overshadow other equally urgent problems of the current stage of human development.

In its most radical, and therefore highly politicized, version, the current energy transition is seen by many, and, alas, not only in Europe, as a rejection of the use of NRER and a transition to the widest possible, if not exclusive, use of RES. The politicization of debate leads to the politicization of climate models. This approach is telling of an unexecting perception of the STP, which provides an opportunity to reduce emissions through the improvement and application of new technologies of production and use (through the whole value chain) of NRER. Thus, there is an artificial (deliberate?) narrowing of the zone of the search for optimal solutions to ensure low-emission development, including the use of NRER, but on a new – low-emission – technological basis.

After the cumulative effects of the world economy's response to the oil price surge of the 1970s came into action, the demand curve for primary and end-use energy began to flatten as a result of the broken correlation between energy consumption and economic growth. As a result, there has been an expansion of supply on the one hand, and a restraint on the growth of energy demand on the other. There was an objectively determined transition from anticipation of "peak supply" to anticipation of "peak demand".

Under these conditions, an additional man-made demand restriction has emerged in the form of the "Paris Agreement," whose stated goal is to fight for climate protection by reducing greenhouse gas emissions, and thus to impose targeted restrictions on conventional global energy development on the basis of NRER. It is generally accepted by many that such energy is the main human-induced pollutant. Therefore, the fight for the climate made it the top priority. More precisely, its rejection.

Before the Paris Agreement, it were economic factors that dominated, which worked within the expanding set of NRER/RES and led to a redistribution of competitive market shares between different NRER/RES, their "economic substitution" was taking place. The Paris Agreement factor introduced a new dimension that became the dominant criterion of preference over the economic one – the climate or "carbon footprint" dimension (cumulative emissions along the entire value chain, thus it would be more correct – terminology does matter – to speak not about "carbon footprint" but about "GHG emissions footprint").

Hence the surge of attention to RES as sources of not only "electrons" – renewable electricity, but also "molecules" – decarbonized gases, primarily so-called "renewable" hydrogen (H_2), produced by electrolysis of water using RES electricity. This has brought to a new level the issues of competition between NRER and RES, where the key question is how to correctly calculate emissions and the length of value chains taken into account in these calculations.

The experience of previous energy transitions and, more generally, the patterns of the evolution of energy markets show that there can be no complete replacement of the conventional energy resources that form the existing structure of the energy balance by a new energy carrier, introduced for one reason or another into the economic turnover. Each successive dominant energy resource occupied a smaller share of the energy balance than its dominant predecessor because substitution of incumbent energy sources by the new ones has been done not on "instead of" but on "in addition to" basis. There is a kind of "equalization" of the competitive shares of "new" and "incumbent" energy resources in consumption: each eventually finds its optimal competitive niche (which can be distorted in favour this or that energy by non-technologically-neutral state regulation providing preferences to this or that energy for whatever reasons). That is, we cannot consider any new energy resource as a possible universal solution or the next dominant energy source (whether RES or H_2 obtained from them).

There will continue to be another redistribution of competitive niches between "incumbent" (in this case, various types of NRER, including nuclear energy, and conventional RES, such as hydropower) and "new" energy resources (solar, wind, and other "new" RES that appear exotic today, hydrogen, and, perhaps, even energy sources unknown today) taking into account new, additionally introduced criteria and man-made restrictions (in this case, under the framework of the climate agenda – such as the "emission footprint", etc.) and the achievements of the STP in response to these new man-made (and, apparently, not final) restrictions (next, this author supposes, could be the "water intensity" of material production).

IV. EU: Hydrogen, "renewable" and that obtained from natural gas, and "technological neutrality"

At first, as the universal solution for the future of energy under the framework of its decarbonization policy in the EU, they envisioned a 100% electrification based on renewable energy under "digital, electrical, renewable" EU future energy vision. In January 2018 this vision was publicly reformulated to "RES electricity plus decarbonized gases". I called this EU energy policy maneuvre/adaptation a "Borchardt turn" – by the name of the then Deputy Director General of Energy Directorate (DG ENERGY) of the European Commission Klaus-Dieter Borchardt who has first announced this is his interview to Florence School of Regulation [12]. This opened a window of opportunities for the search for a new balance of interests between Russia and the EU in the energy and, in particular, in the gas sector based on the low-emission agenda. Among the main "decarbonized gases" and, perhaps, the key one in the EU is considered to be hydrogen. At the same time, despite the declared adherence to the principles of "technological neutrality" in its energy regulation, in the EU there is clearly an unconcealed preference for "green" or (which means the same in the EU) "renewable" H_2, that is, the one obtained through electrolysis of water using RES electricity, which is considered to be as if the only "clean" one in the EU. This is clearly prescribed in the EU

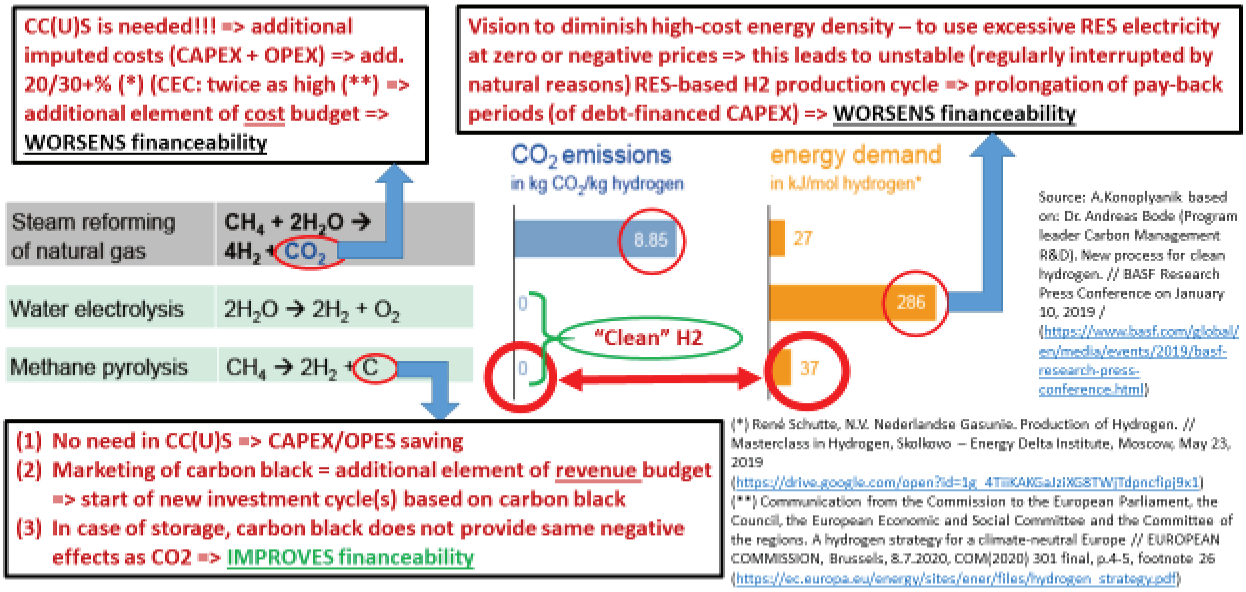


Fig. 2. All other conditions being equal, methane pyrolysis (& similar technologies) have clear competitive advantages against two other key technologies in hydrogen production (MSR+CCS & electrolysis) under technologically neutral regulation.

Hydrogen Strategy [13].

However, there are both obvious disadvantages of "renewable" H_2, and the comparative advantages of H_2 produced from natural gas, both by steam methane reforming (SMR) with the mandatory use of CCUS technology (carbon capture and sequestration and/or commercial use of CO_2 obtained when using the SMR), and methane pyrolysis, in which process CO_2 is not produced (see Fig. 2).

However, at the political level, it is actually already predetermined (as part of the EU Green New Deal unveiled by the European Commission in 2019) that this renewable H_2 is the designated desirable choice in the decarbonization policy. Other technologies of H_2 production are either allowed as temporary companions (unwelcome but involuntary) within the framework of the energy transition for the next ten years or so – until 2030 (SMR + CCUS), or almost (de facto) ignored altogether on one pretext or another (pyrolysis-based group of technologies for obtaining H_2 without CO_2 emissions from natural gas). On this basis a new long-term energy policy of the EU is being built, including in the external economic area, that is, in the relationship with major foreign trade partners. And this transition to "green" ("renewable") H_2 is not only not based on the balance of interests of EU energy consumers and energy suppliers inside and outside the EU, but it is (explicitly or implicitly) imposed on the EU community and its foreign trade partners as the only correct (the only possible) scenario of a hydrogen economy, despite many issues that remain open, questionable, controversial.

However, both within and outside the EU, it is de facto recognized that many aspects of the transition to a hydrogen economy based on "green"/"renewable" H_2 (with respect to its unconditional superiority and priority of such H_2-related decisions, including politically predetermined ones, which have already been taken) are still not elaborated enough. Moreover, much of the hydrogen topic is essentially hype (hard-sell advertising). This is, in fact, acknowledged in the European Commission itself [14] and as part of various high-profile events [15]. There are also more radical views on the current European euphoria regarding the H_2 and its causes, and coming from amongst the professionals. For example, Samuel Furfari, a professional chemical engineer who has worked for 36 years at the European Commission and has spent his entire career in the field of energy and emissions reduction, believes that the "hydrogen illusion" (which is the unambiguous title of his book) that has gripped Europe is among other things a wrong decision used to cover another mistake made earlier – reliance on the advanced development of unstable energy production based on RES. The author believes that the movement along this dead-end path has begun only because it is politically correct, is on-trend, and is secured by money that can be spent on it [16].

"Green" ("renewable") H_2 remains much more expensive than both "blue" H_2 and natural gas (see Fig. 3). Despite the ambiguity of any current estimates (based on different and often unknown assumptions) of the costs of producing H_2 in different countries and their delivery to places of consumption, and the inappropriateness of direct comparisons of such estimates, the gap between the cost levels (order of magnitude of numbers) today is sufficient to assert the absolute economic inefficiency of using technologies for producing "renewable" H_2 as compared to obtaining H_2 from natural gas, and hydrogen technologies – as compared to gas technologies, based on the degree of maturity (commercialization) of these technologies and the price of the energy resource used. And the steps that

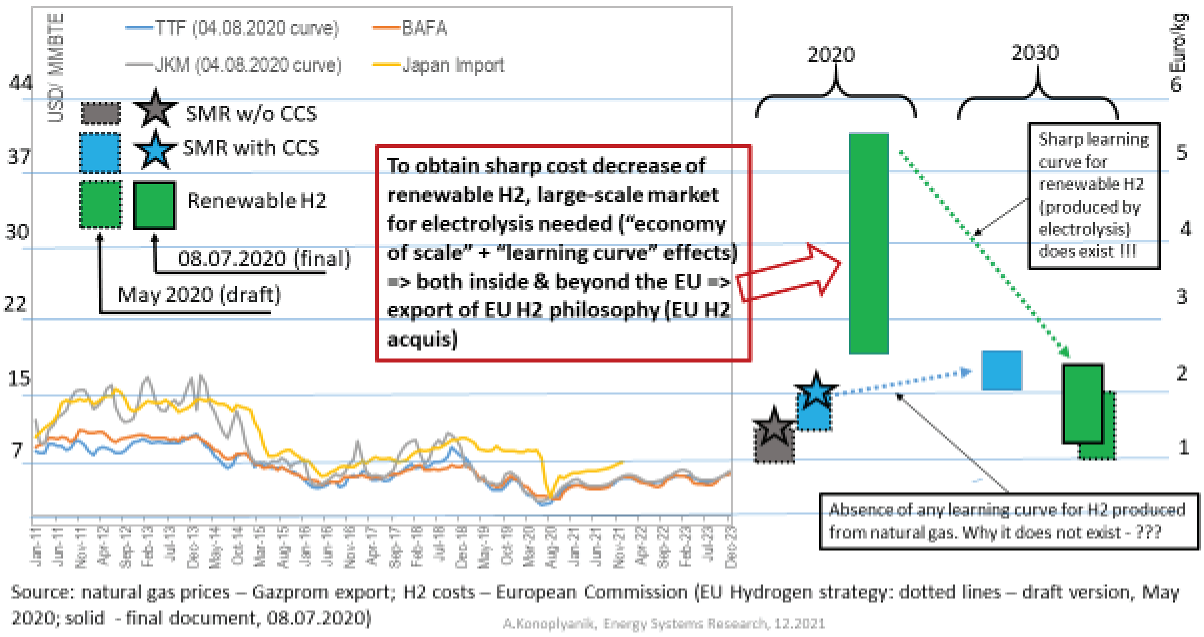


Fig. 3. European Commission's estimated costs of H_2 production by the key technologies (as presented in the EU Hydrogen Strategy as of 08.08.2020) – and natural gas prices.

followed could be characterized by the proverbial "destroy your competitor" and "it does not matter how they voted, it is important how we counted".

This author was unable to get a coherent explanation in the sources of information available to him, or in conversations with European experts (from companies, universities, the European Commission), that would warrant the fact that it is expected (and included in the EU Hydrogen Strategy [13]) to have such a sharp decline in the cost of producing "green" H_2 by 2030, given that the main component of these costs is the price of purchased electricity.

It is clear, and it was repeatedly stated, that the bet is on the purchase of excess RES electricity (otherwise this H_2 ceases to be "green" and "renewable") at zero or negative prices when it is too much sun and/or wind above the demand electricity curve. But in 2019, for example in Germany, the duration of the period of negative prices was only 211 hours of 24 × 365 = 8 760 hours of their annual balance, that is, the electrolyzer will run on excess RES electricity only 2.5% of the time [17, p. 6]. This may explain the prohibitively high production costs of "green" H_2, but it fails to explain why they should fall.

It is also unclear why the European Commission's projections use a "learning curve" for estimating the costs of producing "renewable" H_2, and a steeply declining one for that matter, while for H_2 from natural gas (and the European Commission persists in considering only the SMR+CCUS bundle, continuing to ignore the more economically viable methane pyrolysis), by contrast, it presupposes the rising costs of production of "blue" H_2. In this author's opinion, the remarks that gas prices will grow in the long term (let us leave aside the inevitable market deviations from the trend that take place under any long-term dynamics) are unfounded. In the transition to a supply surplus (the result of the predicted "peak demand" for NRER) instead of the "Hotelling theorem", which ensures that the producer gains the "Hotelling rent" in the case of a supply shortage (due to price equalization with the more expensive substitute energy resource as a benchmark), gas-to-gas competition begins to take place in the market, leading to lower prices. Open questions remain about the price of produced H_2 at the consumer end (by adding the cost of its transport and taxes through the whole hydrogen chain, and what kind of technology is to be used), etc.

There is an overemphasis on H_2 in general and on "green" H_2 in particular, it is overrated as a possible universal solution to the decarbonization problem, which it, in principle, cannot be and will not be – there is no one single "silver bullet". Unrealistic expectations, as we know, can only lead to bigger disappointments in the end. And if the unrealistic expectations regarding H_2 in general and "green" H_2, in particular, are the basis for long-term capital-intensive investment decisions (and there can be no other in this area by definition), the disappointments in the end will be not only and not so much emotional. Much more important will be long-term economic consequences in the form of direct and indirect damage to the EU economy, and – more importantly – to the economy of my own country Russia. Therefore, in order to avoid all sorts of disappointments, to avoid building the country's long-term energy policy on the basis of imported unrealistic or, worse, incorrect expectations related to H_2, it seems necessary to look more carefully and critically at the key arguments regarding H_2 and scenarios of hydrogen cooperation of Russia primarily with the EU.

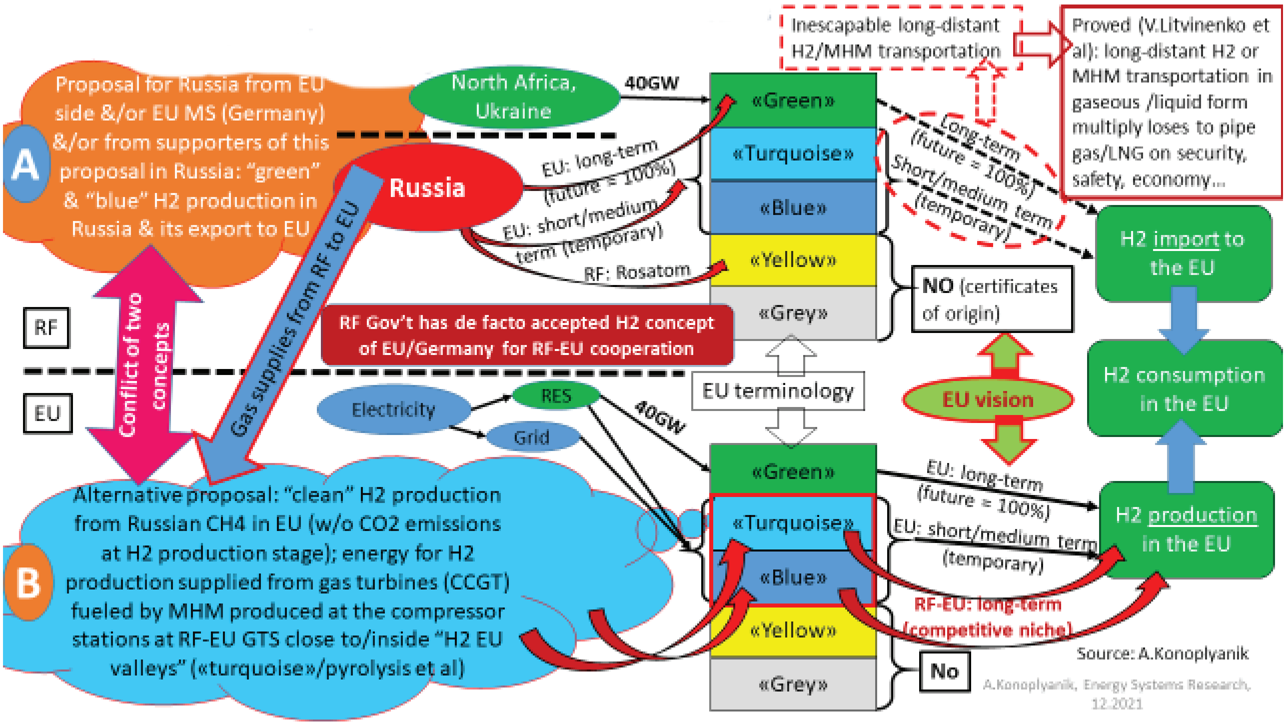


Fig. 4. Russia-EU cooperation prospects in H_2 area as seen by different parties: alternatives for H_2 supply to the EU.

The development of hydrogen technology in Russia will not be able to quickly create sufficient domestic demand for H_2 so as to make it competitive with other energy resources. This author believes that his country is not ready for this today, primarily because of its socio-economic parameters. Therefore, the development of such technologies (considered as zero- or low-emission) as one of the key areas of curbing the growth of global temperature, in this author's opinion, for Russia is not as a priority state task as is for many foreign countries characterized by both higher values of per capita GDP and higher, compared to Russia, levels of energy efficiency in all segments of energy value chains.

So, there is no point in counting on intensive development of hydrogen competences, their rapid scaling based on domestic demand for H_2 (economy of scale and learning curve effect), growth of their not only national but also global competitiveness through the domestic market. But it is also counterproductive to withdraw from global technological competition in this area. Therefore, the initial impetus for the development of hydrogen energy (as one of the components of the country's low-carbon development) should come from the external economic area, using the stated desire of our main trade and investment partners to decarbonize, including the gas industry.

And here is where the point of divergence arises: how to build such external economic cooperation. Which model to use: the one offered by our Western partners (the EU, in particular, Germany), which is also advocated by many domestic "experts" and which the Russian Ministry of Energy and the Russian Government seem to intend to follow (judging by the newly adopted Hydrogen Concept of the country [18]), or an alternative model?

V. The EU-Germany concept of hydrogen cooperation with Russia

Adopted in 2019, the European Green Deal aims to achieve carbon neutrality of the EU by 2050, relying on the development of RES and decarbonized gases, primarily H_2. At the same time in the "Hydrogen Strategy of the EU" of July 8, 2020 [13] the emphasis is made on "renewable" ("green") H_2, produced by methods of electrolysis of water using RES electricity. However, the EU recognizes that the projected volumes of "renewable" H_2 produced domestically by 2050 will not be enough to achieve the zero-emission goal. Therefore, imports of H_2 and its production from natural gas are allowed. The latter is to be achieved exclusively by SMR with the mandatory use of CCUS. There is some tough rhetoric on H_2 from natural gas as only a temporary (unwanted, but necessary) companion to "renewable" H_2.

To make "renewable" H_2 in the EU as cost-effective as possible, European equipment manufacturers need to have a large-scale market for high-unit-capacity electrolyzers both inside and outside the EU. The concept of cooperation with neighboring countries on hydrogen, promoted by the EU, its member states (Germany) and their business associations (the Russian-German Chamber of Foreign Trade [19–21]) is aimed at this. The EU (primarily Germany) proposes to build cooperation on the basis of the development of H_2 production inside Russia and its exports – in pure form or as a methane and hydrogen blend (MHB) to the EU.

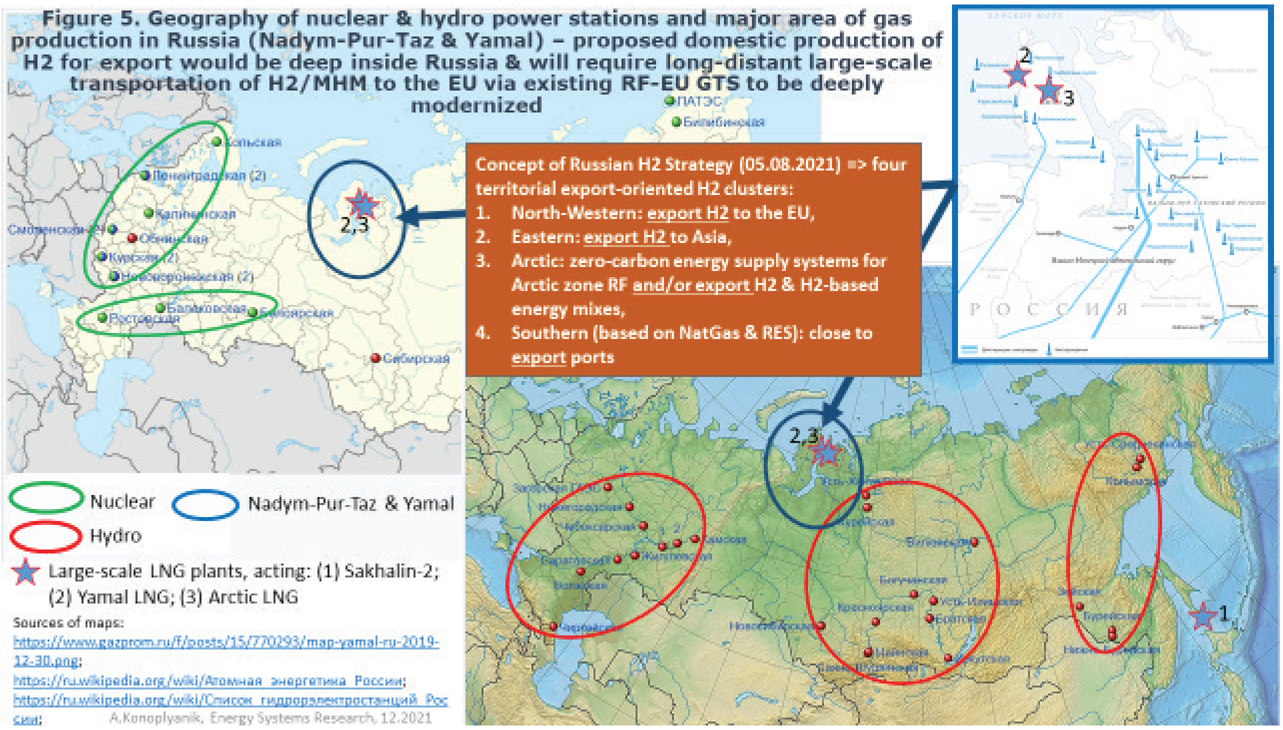


Fig. 5. Geography of nuclear & hydro power stations and major area of gas production in Russia (Nadym-Pur-Taz & Yamal) – proposed domestic production of H_2 for export would be deep inside Russia & will require long-distant large-scale transportation of H_2/MHM to the EU via existing RF-EU GTS to be deeply modernized.

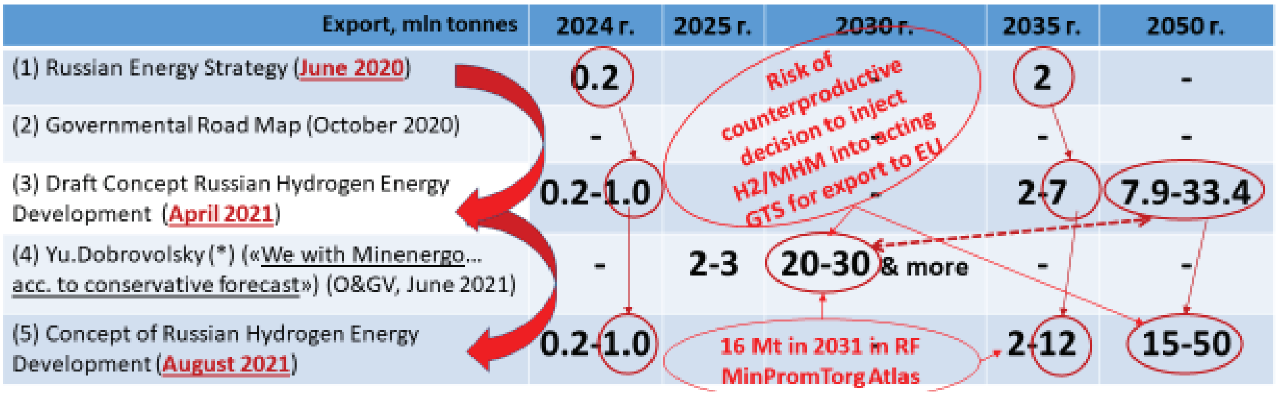
It is proposed to produce H_2 by electrolysis on the basis of excess capacities of Russian hydro power stations (HPPs) and nuclear power stations (NPPs), and by SMR (with CCUS technology) on the basis of Russian gas fields in the main gas production regions (Nadym-Pur-Taz, Yamal) and to inject CO_2 into pay zones of oil fields in Western Siberia to increase oil recovery. Given the location of the proposed H_2 production facilities in the interior of Russia (see Fig. 5), this predetermines the long-distance pipeline transport and deep modernization to make it suitable for H_2/MHB, and in fact complete replacement of the existing cross-border gas transportation system (GTS) Russia-EU throughout its many thousands of kilometers of diversified length.

The main beneficiaries of such a decision will be the European machine-manufacturing industries. First of all, the German electrolyzer manufacturing industry. It needs a thick sales market to reduce unit costs (economies of scale). Within Europe this market is limited. So neighboring countries should be encouraged to produce "renewable" H_2 at home (based on electrolyzers labeled "Made in Germany") and transport it to Europe from there. To support this international model of hydrogen cooperation, the Federal Republic of Germany has allocated 2 billion euros in its national hydrogen strategy [22, p. 3]. It is directly mentioned in the German National Hydrogen Strategy, that among its goals and ambitions are: "Developing a domestic market for hydrogen technology in Germany, paving the way for imports", "Enhancing transport and distribution infrastructure", and especially "Strengthening German industry and securing global market opportunities for German firms", and for this "Establishing international markets and cooperation for hydrogen", "Building up and securing the quality assurance infrastructure for hydrogen production, transport, storage and use, and building trust" and "Regarding global cooperation as an opportunity" [22, pp. 5–7]. Such a model (production of "renewable" hydrogen abroad and importing it from there in the form of H_2, MHB or ammonia) is promoted by Germany with respect to Russia and other countries, such as Saudi Arabia (the German industrial giant Thyssenkrupp is to become the supplier of 20 MW electrolyzers for this $5 billion initiative) [23], Morocco [24], some other African states [25]. This model underpins the EU Hydrogen Strategy, which explicitly mentions three regions – North Africa, the Western Balkans, and Ukraine within the framework of the EU Southern and Eastern Neighborhood Policy [13].

Such an external economic concept is completely in line with the national interests of the EU and individual EU countries and is completely, in this author's opinion, contrary to the national interests of Russia.

VI. Hydrogen cooperation with the EU: mutually exclusive Russian approaches

However, some Russian "experts" voice their support for the EU/Germany vision of establishing hydrogen cooperation with Russia, almost in unison with that for the hydrogen philosophy of Germany (June 2020 [22]) and the EU (July 2020 [13]). Moreover, in this very direction,



Export, mln tonnes	2024 г.	2025 г.	2030 г.	2035 г.	2050 г.
(1) Russian Energy Strategy (June 2020)	0.2			2	-
(2) Governmental Road Map (October 2020)	-			-	-
(3) Draft Concept Russian Hydrogen Energy Development (April 2021)	0.2-1.0		-	2-7	7.9-33.4
(4) Yu.Dobrovolsky(*) («We with Minenergo... acc. to conservative forecast») (O&GV, June 2021)	-	2-3	20-30 & more	-	-
(5) Concept of Russian Hydrogen Energy Development (August 2021)	0.2-1.0			2-12	15-50

***Fig. 6.** Russian Ministry of Energy/Government: increasingly ambitious bet on hydrogen exports, but the issue of getting it to export markets is technically unsolved, and the solutions voiced by "experts" are counterproductive, unprofessional, and ruinous...*

which is counterproductive for Russia, in this author's opinion, the vector of hydrogen energy development has already been formed, which was first unambiguously outlined in the hydrogen section of Russia's Energy Strategy as of June 2020. It says that "an indicator of the solution to the hydrogen energy problem is the export of hydrogen" [26, p. 47]. And later the focus on H_2 exports was strengthened in the Concept of Hydrogen Strategy of the country approved by the Russian government in August 2021 [18]. This explicitly stated the plans for domestic export-oriented H_2 production in the four planned "territorial export-oriented hydrogen clusters" (see Fig. 5) which thus predetermines (and this is how it is explicitly understood in public in Russia and internationally) long-distance transport of H_2 or MHB abroad. And the plans for H_2 exports become more and more ambitious with each revision of the government document without any obvious reason or explanation: from Energy Strategy (June 2020) [26, p. 47] – to the draft Hydrogen Strategy (April 2021 [27, slide 7]) – to the approved Concept of Hydrogen Strategy (August 2021) [18, paragraph 26] (see Fig. 6). Despite the fact that the same source [18, paragraph18] says that "the technologies of transport and storage of H_2 currently used, haven't been tested enough in the industry, have unsatisfactory technical and economic performance, and lead to a significant increase in the cost of H_2".

Nevertheless, many "experts" look at the problem of H_2 transport differently. A.B. Chubais, Special Representative of the President of Russia for relations with international organizations for achieving sustainable development goals, publicly stated three times during June-July 2021 [28–30] that "Russia is able to set the goal of maintaining the status of a "great energy power" with the substitution of hydrocarbon exports with H_2 exports. There is a figure in the European Hydrogen Strategy: in 2030 the H_2 market volume in Europe is 10 million tons. Europe says frankly: this entire volume cannot be generated in Europe alone. We need imports. Its volume is up to about 50%." That means 5 million tons. And now the figures for "potential" Russian H_2 export for 2030 have been increased from about 1.5 million tons in the Hydrogen Section of the Energy Strategy of Russia [26, p. 47] to 4 million tons in the draft [27, slide 7] and to 6.5 million tons (although at maximum) in the Concept of Hydrogen Strategy of Russia [18, paragraph 26] (see Fig. 6). This is more than enough, according to the final document, to cover the entire volume of H_2 imports required by Europe.

Moreover, Chubais urges "to hurry up and not to lose this race to Ukraine", explaining that (July 7) "Mrs. Merkel will pay an official visit to the US in ten days to discuss with Biden the issue of large German-American investments in Ukraine to build a mega-project on renewable energy. The goal is to produce hydrogen and export it to Germany" [31].

So, the bet on H_2 exports to Europe is made, and it seems that the race to get ahead of potential competitors, real and/or imaginary, may begin (is beginning?). How to make this bet pay off? The answer for the authors is obvious: to produce H_2 in Russia (first of all "green" H_2 produced by electrolysis but it can also be "blue" produced from natural gas) and transport it to the EU through the existing GTS. A.B. Chubais has repeatedly stated: "Experts unanimously say: the existing unified GTS is suitable for using at least 10% of the throughput capacity for H_2 transport. Without a deep modernization of the GTS" [28].

A number of experts, mostly "political scientists", suggest converting Nord Stream 2 to H_2 or MHB transport first, and then, perhaps, build the third or then, perhaps, even the fourth Nord Stream for H_2 (for example, a series of publications by V.B. Belov, Deputy Director of the Institute of Europe of the Russian Academy of Sciences, specialist in German issues [32–34]). Others (e.g., V.A. Karasevich and I.G. Rodichkin) believe that "blending 5–10% of H_2 with methane will lead to a positive image effect for the pipeline "Nord Stream 2", caused, in particular, by a lower carbon footprint of MHB in comparison with methane" [35]. And some "experts on the subject" fail to see any difference between transporting H_2 and methane. According to E.A. Telegina, a corresponding member of the RAS and the dean of the International energy business department of Gubkin Russian State University of Oil and Gas, "the gas transport infrastructure can be easily adapted for hydrogen transport ... Nord Stream 2, the current system, can be quite easily transformed for hydrogen transport ... the transport infrastructure can be easily transformed technologically, because it is the same gas under pressure, which flows through pipeline systems" [36].

However, it has been convincingly proved that long-distance transport and storage of H_2/MHB in gaseous or liquefied form due to objective physical and chemical reasons and unresolved engineering problems is by a wide margin inferior in reliability, safety, and economic feasibility to long-distance transport and storage of natural gas in gaseous form or as LNG. This author asserts (together with the experts he knows, including those from the Mining University in St. Petersburg (SPb), Gazprom, specialized technical – not "political" – institutes of the Russian Academy of Sciences, etc.) that long-distance transportation of H_2 or MHB via the current RF-EU GTS is counterproductive if compared to the transport of pipeline gas.

As a chemical element, H_2 is the enemy of steel structures (stress corrosion, hydrogen embrittlement). The physical and volumetric characteristics of H_2 reduce the overall efficiency of the energy system compared to similar hydrocarbon solutions. The energy derived from the same volume of H_2 is 3.5 times less than from methane. And the efficiency of pipeline gas transport depends directly on the volume of the product, hence the density of the gas. The work of V.S. Litvinenko and colleagues (Mining University of St. Petersburg) [37] shows that with an increase in the volume fraction of H_2 from 10 to 90% the density of MHB decreases more than fourfold. In this case, the energy needed to compress the mixture increases by a factor of 8.5 if this fraction in the MHB is increased from zero to 100%. The current GTS can technically handle 10% of H_2, but this will lead to disastrous consequences for the country with respect to its deep technical modernization (both line pipes and compressor equipment), disruption of technical integrity, and contractual issues.

According to colleagues from "Gazprom vodorod" ("Gazprom Hydrogen"), the dilution of an expensive product (H_2) in a cheaper gas does not form the optimal business model, because it is not clear how then to monetize the delivered product (MHB), because one needs to build facilities for the separation of H_2 (membranes, etc.) at the place of its delivery to the consumer, commensurate in cost with the production of H_2 directly at the place of consumption. Moreover, it is unclear why one should reduce the price of a premium product (H_2) by diluting it with a cheaper one (natural gas). Moreover, an assessment of the emission footprint along the entire value chain shows that the use of the blend does not contribute much to the reduction of emissions, i.e., 10% of H_2 in the MHB will do nothing of consequence in terms of achieving the EU climate goals.

Such a "modernization" of the existing GTS to adapt it for H_2 could be comparable in scale to the cost of the U.S. Strategic Defense Initiative (SDI) threat countermeasures in the USSR in the 1980s and its ruinous consequences for the country. As is known, the U.S. SDI ended up being a well-organized disinformation campaign, but the costs of countering it were ultimately beyond the means of a country already overburdened with debt and unaffordable internal costs and only accelerated, in this author's view, the destruction of the USSR economically.

VII. Energy transition driven by half-truths

The actual support by a number of Russian experts for the hydrogen concepts of Germany and the EU, in this author's opinion, fails to take into account the fact that the latter are built on half-truths. The decarbonization of the European economy is accompanied by a deliberate distortion of the frame of reference within which the public consciousness in the EU is formed and the relevant political directives are adopted. Which are then enshrined in legislation and set the direction for long-term capital-intensive investment decisions that define the framework for development for many years. One of the significant distortions is the comparison of the CO_2 emissions of NRER industries and the cleanest of them (natural gas) to the same of RES.

In the EU, natural gas is considered to be a bad solution for the energy transition in principle, because it contains carbon (C) molecules, which as is inevitably (at any rate) turn into molecules of climate-damaging (harmful) CO_2. This approach, however, denies the very nature of the STP, which can both help reduce CO_2 emissions to a level acceptable and comparable with that of other advanced technologies (again, the question is how to count emissions) and find technological solutions to prevent CO_2 from forming. One such solution is the use of pyrolysis technologies to produce H_2 from natural gas in the absence of oxygen and, therefore, without CO_2 emissions. The EU Hydrogen Strategy, unfortunately, simply ignores such technologies: in its text the word "pyrolysis" occurs only twice, and, moreover, one time it is used incorrectly (for it seems to equates SMR+CCUS and pyrolysis, talking about incomplete – in both cases – utilization of CO_2 at the 90% level), while the second time it is mentioned in passing only [13, p. 4, 17].

On the other hand, it is argued that, unlike natural gas, renewables are clean – indeed, as if the only clean source of energy, because they do not emit greenhouse gases as part of their production cycles. Therefore, renewable H_2 produced using RES is also the only clean H_2. And this incorrect assumption is embedded in the EU Hydrogen Strategy – in the section "Definitions" [13, pp. 3–4] – as a kind of already established fact.

In the EU Hydrogen Strategy, when determining the so-called "carbon footprint" of RES and renewable H_2, material-intensive (and therefore energy-intensive, accompanied by increased CO_2 emissions) industries for the production of equipment for RES electricity generation

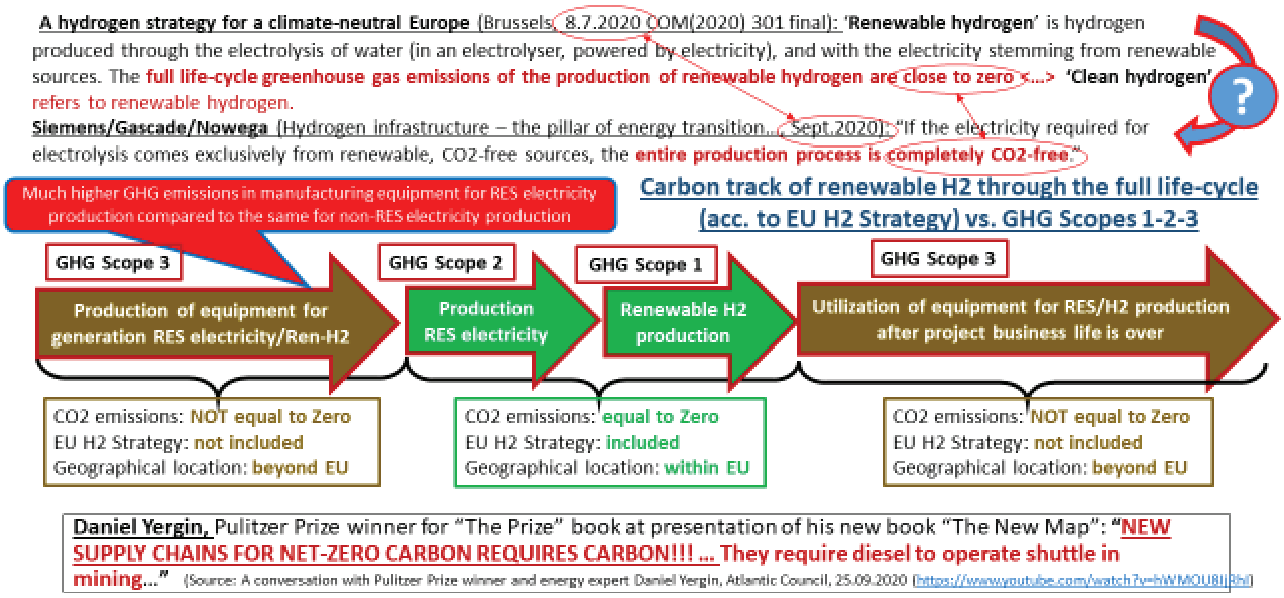


Fig. 7. What is clean energy? Depends on how you calculate/consider it… Wrong perceptions as if Ren-H_2 is the only clean H_2 and, moreover, that it is clean at all => Energy Transition based on semi-truth…

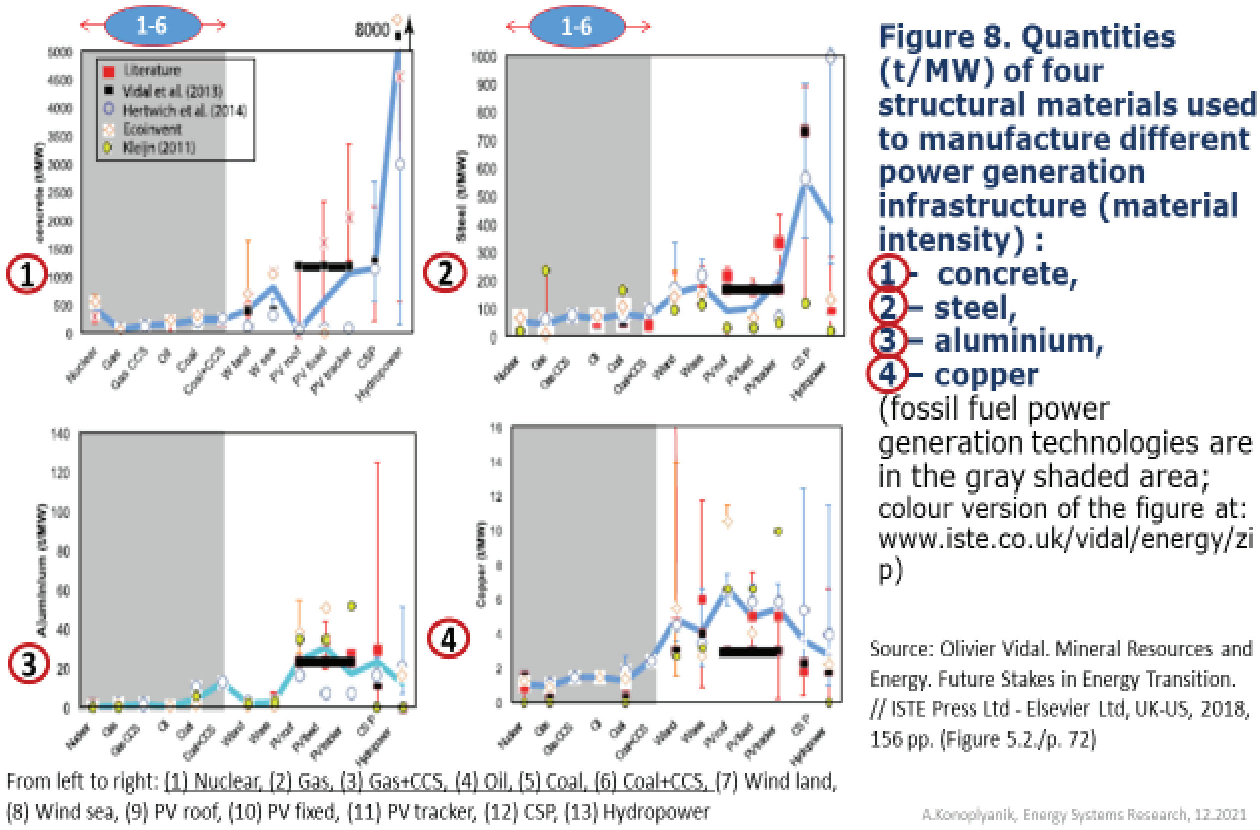


Fig. 8. Quantities (t/MW) of four structural materials used to manufacture different power generation infrastructure (material intensity): 1 – concrete, 2 – steel, 3 – aluminium, 4 – copper (fossil fuel power generation technologies are in the gray shaded area; colour version of the figure at: www.iste.co.uk/vidal/energy/zip).

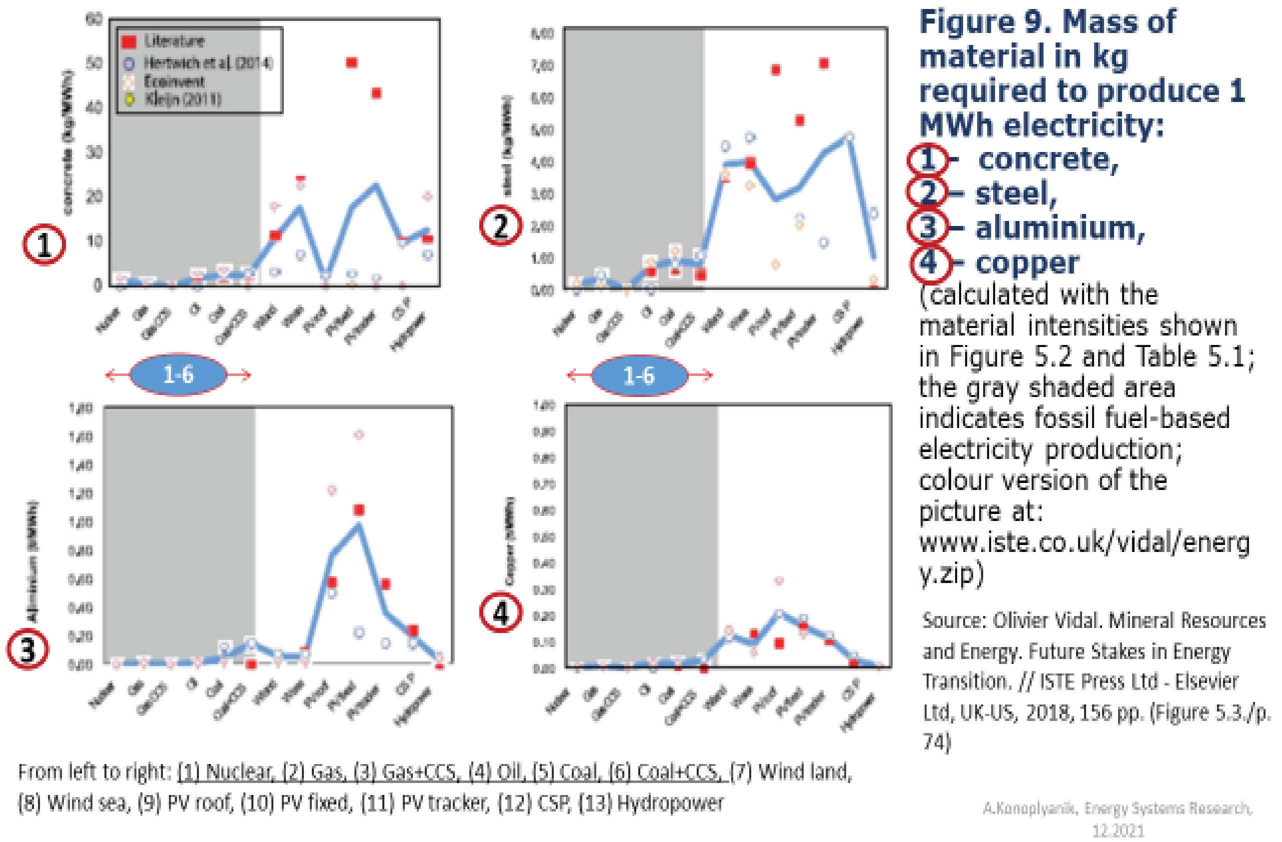


Fig. 9. Mass of material in kg required to produce 1 MWh electricity: 1 – concrete, 2 – steel, 3 – aluminium, 4 – copper (the gray shaded area indicates fossil fuel-based electricity production; colour version of the picture at: www.iste.co.uk/vidal/energy.zip).

are excluded from consideration. As well as production of equipment for H_2 production (electrolyzers) (see Fig. 7). This significantly changes the comparative picture of cumulative CO_2 emissions over the full production cycle of various H_2 production processes (electrolysis, SMR+CCUS, methane pyrolysis) as part of the EU policy decision-making system. At the same time, electrolysis is about 4–5 times (Gazprom data [38]) or even 10 times (BASF data [39]) more energy-intensive process than H_2 production from natural gas. Therefore, proportionally more electrolyzers and RES production capacity are needed (even more so given the low installed capacity utilization factor (ICUF) of RES in Europe: in Northern Germany the ICUF of wind turbines on land is 1 900 hours/year or 21%, and those sea-based – 4 500 hours or 51% [17, p. 6]). Therefore, the production of both types of capacities will be accompanied by higher emissions. And green, or renewable, H_2 ceases to be clean.

As Daniel Yergin, the Pulitzer Prize winner for “The Prize” book has said at the presentation of his new book “The New Map” at Atlantic Council in September 2020: “New supply chains for net-zero carbon requires carbon! They require diesel to operate shuttle in mining…” [40].

Thus, the environmental advantage of each energy source is determined by how the emissions are counted. If we consider only the direct CO_2 emissions from the production of renewable H_2 by electrolysis of water (the so-called “Scope 1” under greenhouse gas emissions and from the production of RES electricity (wind, solar, hydro) (“Scope 2”), then the environmental friendliness of these production processes must be recognized. If we also include the production of equipment for production of RES electricity and/or green H_2 (the first part of “Scope 3”), the picture changes drastically. Both RES electricity and renewable H_2 will cease to be emission-free. And this picture will change even more radically, and RES electricity and renewable H_2 will cease to be “emission-free” even more, if we also include the phase-out and disposal of equipment after the end of the lifetime (life cycle) of the project (the second part of “Scope 3”) (see Fig. 7).

Failure to account for “Scope 3” emissions can significantly change the entire overall picture of emissions and, more importantly, accounting for them can turn (is turning?) all business processes built on so-called “zero-emissions” technologies into “non-zero emissions” ones. The example of Apple, which voluntarily made its data available to the public, shows that, as in the case of renewable H_2, Apple’s emissions under “Scopes 1 and 2” are close to zero. However, emissions under “Scope 3” are quite large, and within this group, the equipment manufacturing stage accounts for three-quarters of emissions of all three “Scopes” [41].

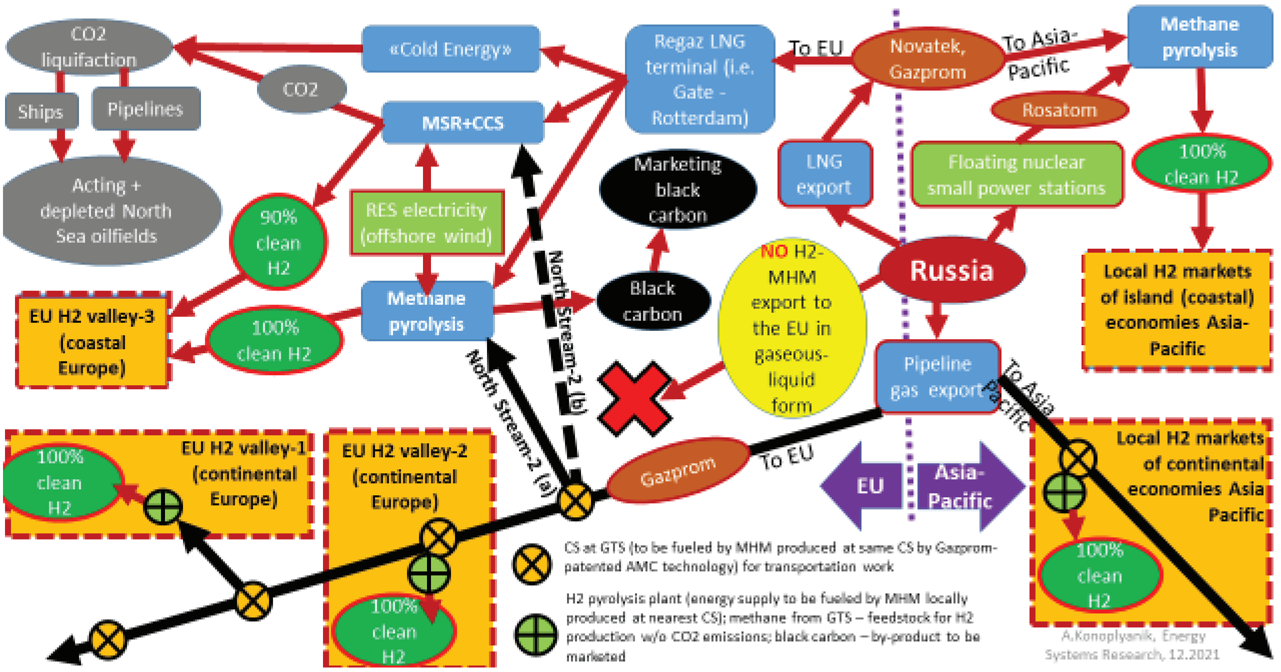


Fig. 10. Alternative concept for export-oriented segment of Russian hydrogen energy economy – based on clean H_2 (w/o direct CO_2 emission) from natural gas (Konoplyanik's vision).

A study by Olivier Vidal [42] summarizes data on four basic construction materials (cement, steel, copper, aluminum) and 13 power generation technologies (six of them based on NRER and seven based on RES). It shows many-fold excess of material inputs for all four materials in the production of equipment for electricity generation based on RES against the corresponding technologies based on NRER: both per unit of capacity (see Fig. 8) and per unit of electricity output (see Fig. 9). In the case of hydropower plants, for example, the consumption of cement per unit of power is just off the scale.

Thus, if backed by a valid scientific approach, green or renewable H_2, free of direct CO_2 emissions, ceases to be "the only clean" one (as declared in the EU Hydrogen Strategy [13]) in comparison with H_2 from natural gas, especially that produced by pyrolysis, on which Gazprom relies and in the production of which there are also no direct CO_2 emissions. However, a distorted frame of reference is used, alas, to justify the exclusive acceptability of specifically "green", or "renewable" (and significantly more expensive), H_2 as the only way to decarbonize the EU in the long-term (short-term "blue" H_2 is involuntarily allowed to accompany "green" H_2).

Therefore, in this author's opinion, the concept of the proposed hydrogen cooperation based on EU (or German) models is unacceptable for Russia, because it is built on half-truths and are not in line with the national (sovereign) interests of my country. In particular, those of the tasks of effective monetization of Russian natural gas resources and existing production assets, primarily the EU-Russia cross-border gas transportation system. Although, to reiterate, such a concept fully reflects the national interests of the EU, Germany, and the businesses of these countries.

VIII. The mutually acceptable alternative: this author's position

Is there an alternative that is built on a balance of the interests of the parties? I assert that there is one. On the basis of existing groundwork solutions, including those by Gazprom PJSC, this author proposes the following alternative concept for the development of EU-Russia cooperation in the hydrogen area [43–46]. It is based on the export of Russian natural gas to the EU both via the existing Russia-EU GTS and in the form of LNG, and the production of H_2 inside the EU in areas of advanced demand growth ("hydrogen valleys") by methane pyrolysis (or similar technologies for producing "clean" H_2 – without direct CO_2 emissions) throughout Europe and/or SMR+CCUS in coastal areas of Northwest Europe (see Fig. 10).

In the case of LNG deliveries to regasification terminals on the Northwest European coast, as well as pipeline gas deliveries via the Nord Stream pipelines, H_2 production at pyrolysis or SMR plants near gas delivery points can use RES electricity from offshore wind farms in the North Sea. CO_2 released in the course of the SMR process can be liquefied using the "cold energy" released during LNG regasification and then, as liquid CO_2, supplied by tankers or through pipelines running in the reverse direction for re-injection into pay zones of active oil fields and/or depleted deposits on the North Sea shelf. With H_2 production using methane pyrolysis methods and similar methods free of CO_2 emissions (the first such pilot plants are to appear in Russia by 2024 in accordance with the Plan "Development of Hydrogen Energy in the RF to 2024" [47]), opportunities for H_2 production from Russian natural gas are dramatically expanding in continental Europe.

In this case, the natural gas supplied via the EU-Russia GTS will be used for three purposes. First, traditionally, as an energy resource for performing transport operations. At compressor stations (CS) on the routes of Russian gas transport to the EU, methane will be converted into MHB (Gazprom's patented technology of adiabatic conversion of methane [48]), which will be used at the same CS as fuel gas (instead of methane) for further gas pumping through the network. According to Gazprom, this results in a one-third reduction in CO_2 emissions at the CS [48]. No transportation of MHB through the GTS will take place – production of MHB at the compressor station will be only in the volumes required for the CS's auxiliary needs. Secondly, as a feedstock to produce "clean" (with zero CO_2 emissions) H_2 from methane. This is a new niche for Russian gas with high potential demand in the European market. Pyrolysis plants should be located near CSs and aim to meet local demand (rather than common European demand, to minimize the need for long-distance transportation of hydrogen) within the nearest "hydrogen valleys" of the EU. This means that the development of commercial pyrolysis plants should be based on the modular principle of their use – the assembly of plants (as in a set of interlocking Lego pieces) with a capacity adequate to the level of demand for H_2 within a given "hydrogen valley". Third, as an energy resource for the production of "clean" H_2 from natural gas at these pyrolysis plants. Fuel for the gas turbines of the corresponding capacity will be MHB produced in the area of the nearest CS by the adiabatic conversion of methane technology.

In this author's opinion, this is a mutually acceptable option for cooperation between Russia and the EU in the field of hydrogen energy (in terms of production of "clean" H_2). This is a cheaper decarbonization option for the EU. And it provides additional monetization of the natural resources of Russian gas. This is the direction that it is necessary to continue to work in with colleagues from the EU. What we have already been doing within the framework of the EU-Russia Gas Advisory Council's Work Stream on Internal Market Issues [49].

The article reflects the author's personal point of view. Some of the article's points are presented in more detail in the author's papers [43–46 etc.] and are available from his website at www.konoplyanik.ru.

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Professional biography of Prof. Dr. **Andrey A. Konoplyanik can be found** at his website http://www.konoplyanik.ru/en/, as well as, at separate pages, his publications, both monographs and articles, presentations and TV/radio-interviews & commentaries.

Innovative-Technological and Structural-Organizational Transformations of Electric Power Systems: Changes in the Main Properties, and Research Lines

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***Abstract* — This paper discusses one of the most significant areas of systems research in energy that covers the study of the main properties of large-scale energy systems. An emphasis is on the electric power systems, which are currently undergoing organizational-structural and innovative-technological transformations. The evolution of classifications and structures of the main properties of energy systems is analyzed, and interpretation of these properties and the extent to which they manifest themselves in electric power systems in the period before the transformation processes and during the transformation period are given. Findings suggest that the properties had a rather capacious interpretation, which enabled the description of significantly different energy systems, including traditional vertically integrated and emerging new centrally distributed ones. For this reason, there was no need to introduce any new properties, although they can appear in the future. This study examines various transformation processes in the electric power industry and analyzes their influence on the levels of manifestation of properties. The transformation of energy systems and their features requires that the methodology and research tools be refined. Specific directions for such a refinement are proposed in this paper.**

***Index Terms*: Systems research, vertically integrated and centrally distributed power systems, classifications, properties, transformation, methodology.**

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I. Introduction

The research into the properties of large-scale energy systems (LESs), including electric power systems (EPSs), has a long and rich history. In [1], two main goals of studying the LES properties are formulated: 1) understanding the general LES control principles, provisions, and rules arising from individual properties or some combination of theirs; 2) considering the LES properties in mathematical modeling of energy systems to determine an appropriate type of models, specific algorithms and relationships. This paper addresses rather general properties inherent in various energy systems. There are two groups of properties [1]. The properties of one group are inherent in the systems regardless of people's will (for example, the property of incomplete information), the other group is necessary for the system to effectively perform its functions (for example, cost-effectiveness) and LES should be endowed with them in the process of creation. Both groups of properties are objective: the first is objectively inherent in LESs, the second is objectively necessary for LES.

Electric power systems are among the most significant LESs, which integrate other energy systems through their external fuel connections. The structural-organizational and innovative-technological transformations that are taking place in modern EPSs throughout the world considerably alter the systems themselves and affect their properties, and not always in a positive way, which requires research of such an impact, and the development and subsequent implementation of appropriate organizational, economic, and technical measures in EPSs and their control systems.

As will be seen below, the authors of [1–3] introduced a very comprehensive definition of properties, which expands their interpretation and allows using the same properties and their combinations to describe significantly different structures of energy systems, including, for example, traditional vertically integrated and new centrally distributed ones. Thus, it becomes possible to characterize the properties of current and future energy systems without

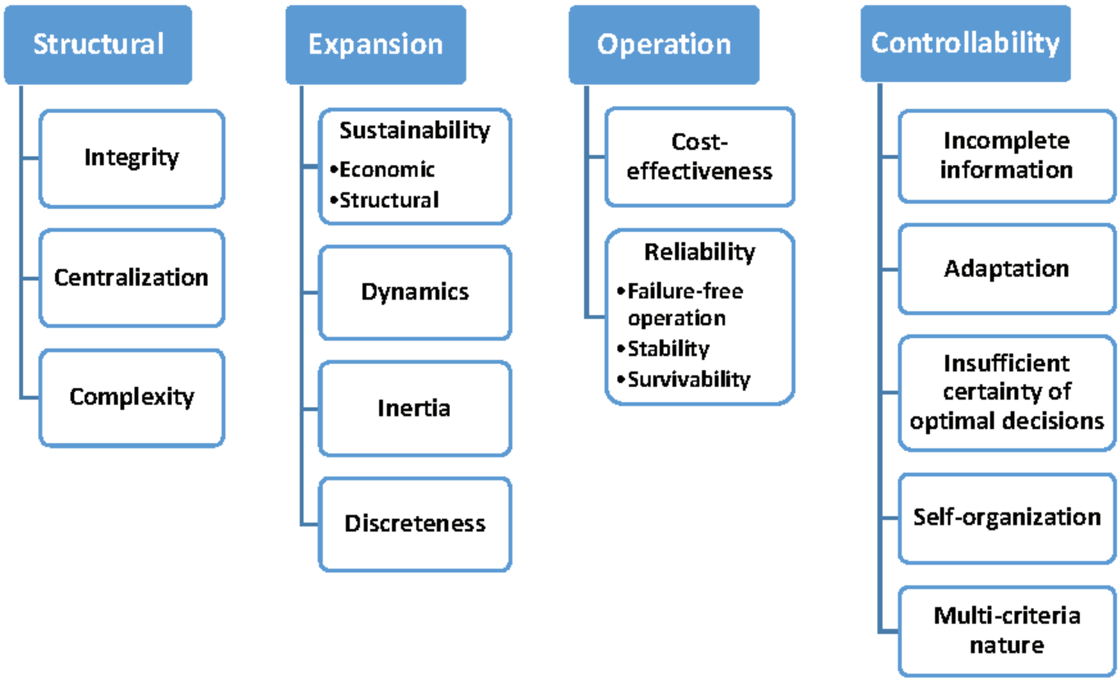


Fig.1. The classification of LES properties [2].

the obligatory updating of the composition of these properties, although it should not be excluded from the consideration.

This work does not claim to comprehensively cover the specified issues and, in this stage, does not aim to formulate an updated set of the energy system properties with their possible classification, adequate to the current conditions. We analyze the main LES properties given in the previously created classifications [1–3], their interpretation in terms of traditional EPSs, changes in these properties in the context of EPS transformation, and the establishment of centrally-distributed cyber-physical energy systems (CD CP EPSs). This paper also presents the lines for further research to provide the basis for creating such systems, given their transformed properties.

II. Evolution of the classification and composition of the main properties of large energy systems

A. The first classification of the main LES properties

The composition of the main properties of LES is a controversial issue, and different authors classify them differently. Academician L.A. Melentiev proposed grouping the properties by highlighting specific individual properties in each group. According to this approach, a two-, three-level hierarchy of properties was built. Originally, he proposed 4 groups of properties (Fig. 1) [2].

Structural properties reveal the essence of hierarchical systems in three closely interrelated properties: a) the integrity of individual systems/subsystems; b) centralization of control; c) the complexity of the hierarchical structure. LESs always have a hierarchical structure, i.e., include interconnected hierarchical systems united by vertical and horizontal links. There is an optimum combination of integrity and centralization. In a planned economy (for which the specified classification of properties was developed), the level of integrity of individual systems is lower, whereas the centralization of their hierarchical structure is higher.

The group of expansion properties characterizes the growth/expansion of any progressive system. Stability is understood as an ability of a system in motion to maintain its structure and properties. In terms of LES, we can consider the properties of *economic and structural stability*. Economic stability is understood as a system's feature under which its significant structural differences are characterized by considerably smaller changes in the costs of its expansion. Structural stability is the ability of a developing system to maintain its structure as a whole. The property of *dynamics* is interpreted as the influence of the current state on the future one and vice versa. *Inertia* is the property of a system to resist external and internal impacts aimed at changing its motion. The inertia of a system depends on the inertia of its components, the inertia of its controls, and the level of system stability. The high capital intensity of LESs, their links with mechanical engineering, metallurgy, transport, the construction industry, significant time spent on the construction of power facilities and related infrastructure cause their great inertia, which manifests itself in the impossibility of dramatically increasing production volumes in a short time, and changing the structure of capacities and fuel and energy balance as a whole [4]. In [1–4], the inertia feature was considered only in the economic sense, for this reason, only such an interpretation is given here. Further, inertia, as well as some other properties, will be considered from a technical *perspective. Discreteness* reflects the objective tendency towards the concentration of generating and transmission capacities in the power industry (the growth of the unit capacity of power units and power plants in general, the transition to higher voltage levels of power transmission lines with an increase in their transfer capability) and, is thus closely related to the inertia.

The operation properties include cost-effectiveness and reliability. *Cost-effectiveness* is the property of a system to carry out its functions with minimum costs under given restrictions, including environmental ones. Reliability is the property of the system and its components to perform the specified functions while maintaining the preset indices. Reliability includes such properties as *failure-free operation*, i.e., continuous operability during a given time, *stability*, i.e., the ability to restore the initial state of equilibrium during systematic short-term disturbances, and survivability, i.e., the ability to restore equilibrium during large disturbances.

The group of controllability properties characterizes the specific objective properties of LESs as objects of control and study. These include the property of *incompleteness/ambiguity of information* about the system. According to this characteristic, along with part of the information that can be considered as deterministic, a significant part of the information is probabilistic and, hence, indefinite. The property of *adaptat*ion is associated with the new components appearing in the system for its development under changing external conditions and with the time required for restructuring the system. The property of *insufficient certainty of optimal decisions* about the LES operation and expansion characterizes the impossibility of finding unambiguous optimal decisions on the control of the system. This property is in close interaction with the hierarchical structure of LES, the properties of *stability, inertia*, and others. The property of *self-organization* is the LES's ability to choose and implement the decision to preserve the nature of interaction with the "outside world" under changing conditions. The *multi-criteria nature* is understood as the property of LES to function optimally and develop under the influence of criteria and constraints that differ at different hierarchical levels. The main criterion is usually the economic one, and the rest of the criteria (environmental, social, and political) are either used as additional or set as constraints.

B. The second classification of main properties of LES

In his later monograph, L.A. Melentiev already proposed three groups of basic properties (Fig. 2) [4]. This classification of properties was simplified compared to the previous version. The properties of expansion and operation were integrated into one group of the properties of motion. Some properties disappeared, to be more precise, they were expressed through other properties, and, in general, the range of properties significantly shrank. Nevertheless, the two-, three-level hierarchy in the classification of properties was preserved.

As for the group of structural properties, in the new classification, they are combined into one property of *the hierarchical structure centralization*. At the same time, the "negative" relationship between the integrity and centralization of systems remains in the sense that the higher the integrity, the lower the level of centralization, and vice versa. Additionally, the duality of the property of the hierarchical structure centralization is specified, i.e., there is centralization in terms of material energy links among sources, transmission and distribution systems, and energy consumers, as well as centralization of bodies within the control system. The integrated group of *motion* properties includes the properties of *dynamics, flexibility, and cost-effectiveness*, with flexibility including the features of *inertia, adaptation, and reliability*. Interpretation of the property of *dynamics* remains the same as in the previous classification. This feature, however, is considered in conjunction with structural and economic *stability*, although the second classification does not contain this property separately (while the first version of the classification highlighted the property of stability). The *flexibility* property was not mentioned in the previous version of the classification at all, but it is closely related to the *adaptation* property, which was included in the first version of the classification. This relation was studied in detail in [5]. The second classification views adaptation as a property that concretizes flexibility. Flexibility is understood as the ability of a system to change its structure at the required speed to ensure normal expansion and operation under possible disturbances. Apart from adaptation, the properties concretizing flexibility include inertia and reliability. These properties were also present in the previous classification. However, inertia belonged to the group of expansion properties, and reliability - to the group of operation properties. In the new classification, however, with the groups of expansion and operation properties integrated into one group of motion, these properties acquired a broader interpretation, covering both the operation and the expansion of LES. The property of cost-effectiveness was previously in the operation group and in the expansion group as economic stability. It now applies equally to the LES operation and expansion. The group of controllability properties was significantly reduced and now includes only the insufficient certainty of optimal decisions and multi-criteria nature.

The new classification of properties does not contain the property of information incompleteness, although it is indirectly present in other properties, such as flexibility and adaptation, insufficient certainty of optimal decisions.

C. The main properties of LES

Later, in [1], it was noted that given the complexity and diversity of the actual relationships between properties as well as the existing ambiguity in the signs by which the

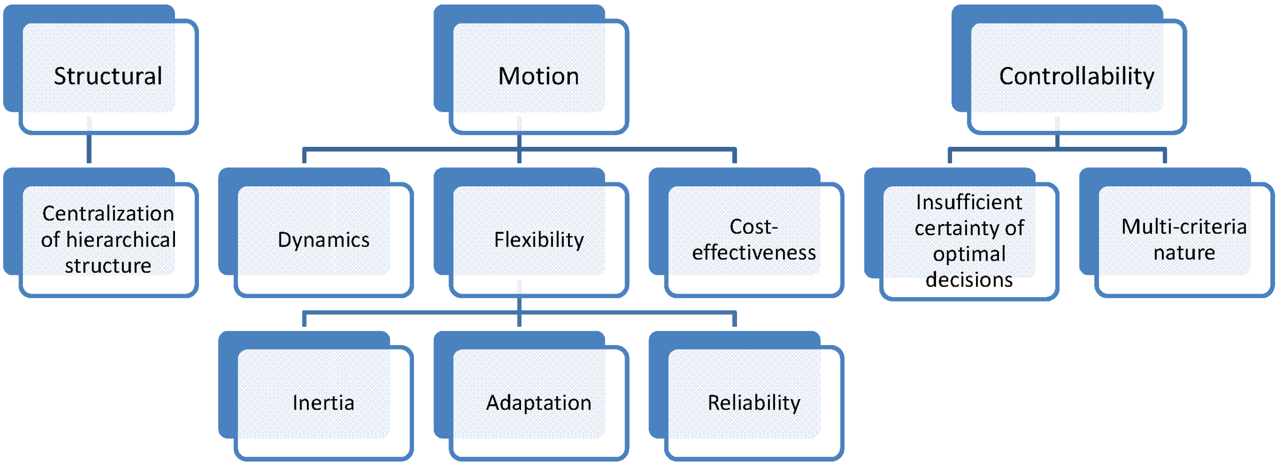


Fig.2. Classification of LES properties [4].

LES properties can be classified, in this stage of research, it is advisable not to group the properties but only establish their composition, i.e., indicate the main properties that are inherent in or needed by LESs. Table 1 shows the main (generalized) central properties characteristic of various LESs. According to [1], the given set of basic properties can be considered "open" and include new properties in the future. The range and the definitions of individual properties should not be regarded as final and generally accepted.

Almost all of the properties presented in Table 1 were indicated in the above classifications of properties by academician L.A. Melentiev. In the terminology of his classifications, the first two properties of *integrity and autonomy* are structural. In this case, however, they have a slightly different interpretation. Whereas earlier, the property of integrity characterized the LES subsystem, i.e., its "separation" from this system, now it characterizes the entire LES. The property of autonomy refers to the LES subsystems and characterizes the presence of their objectives. Together, these two properties describe the structure of LES, its complexity, and its hierarchical structure.

From these two properties considered together, it follows that there should be a rational combination of centralization and decentralization of control, and also coordination of its objectives at all levels of LES hierarchical structure. Thus, even then, it was assumed that LES could be not only a system with strong vertical centralized links but also a system with horizontal links and a "centrally distributed" structure. The property of the *hierarchy of decisions* is formally new, but earlier, it was part of the structural properties and characterized the hierarchy of the control system for the LES operation and *expansion.*

Information incompleteness and cost-effectiveness were previously included in one way or another with similar interpretations.

The *reliability, dynamics, multi-criteria nature, inertia, and adaptability* properties indicated in Table 1 were considered earlier. Their interpretations have changed in some cases.

Reliability was previously considered part of a group of motion properties and covered both the aspect of operation and the aspect of expansion. In our case, this feature is considered in terms of operation alone (as in the second classification by L.A. Melentiev). Reliability includes several single properties, including *failure-free operation, maintainability, survivability, and others*. The interpretation of *the multi-criteria nature*, on the contrary, has been expanded. Multi-criteria nature means not only the presence of several criteria for justifying decisions (economic, environmental, etc.) on the LES expansion and operation but also the presence of their goals for LES subsystems at different levels of the hierarchy. This expands the interpretation of LESs and allows them to be considered not only as centralized vertically integrated systems but also as systems with horizontal links, which has already been noted.

The property of inertia was previously interpreted as the ability to withstand external and internal impacts, whereas Table 1 interprets it as a response to disturbances (including control) with a delay. The manifestation of this feature in the aspect of the expansion, as mentioned earlier, is due to the high capital intensity and long periods of construction of power facilities, and, in addition, the presence of close external ties of the energy sector with other, also inertial, sectors of the country's economy (power plant engineering, geological exploration, etc.). In terms of operation, inertia can be associated with equipment maneuverability, which rises with decreasing inertia. The property of *adaptability* is presented in the "cybernetic" interpretation, which was also used in previous classifications of properties. This interpretation, however, is supplemented by the consideration of adaptation as the ability of LES to adapt its motion to new short-term external and internal disturbances. In this interpretation, *adaptability* is closely related to the property of *flexibility* (which is not presented

Table 1. Main properties of LES [1].

Properties	Definition
The integrity of the system	Unity and the presence of common expansion and operation goals, a central control body
Subsystem autonomy	The relative independence of subsystems the presence of their control bodies, and their expansion and operation goals
Hierarchy of decisions	The objective presence of a set of interrelated decisions to be made in a definite sequence and with the necessary lead time to manage LES expansion and operation, as well as the need to resolve a set of issues to justify these decisions
Incomplete information	The impossibility of obtaining the initial data necessary to unambiguously determine the past, current, or future state of the system
Cost-effectiveness	Performance of its functions with minimum costs of direct and materialized labor
Reliability	Performance of specified functions in a predefined volume under certain operating conditions
Dynamics	Mutual influence of the system's states at different moments (intervals) of time (the present state on the future one, and vice versa)
Multi-criteria nature	The presence of several criteria (goals) for assessing the effectiveness of the system operation and expansion, as well as the discrepancy between the goals (criteria) of subsystem control at different levels of the hierarchy
Inertia	The ability of the system to respond to external and internal (control) actions with a delay
Adaptability	The use of new information to adjust behavior and structure to optimal ones

Table 2. Characteristics of the main properties of EPS during the period of their centralized control.

Property	Characteristic
System integrity	High
Subsystem autonomy	Low
Hierarchy of decisions	Branched decision hierarchy
Incomplete information	Available
Cost-effectiveness	High
Reliability	High
Dynamics	Is present
Multi-criteria nature	Low level of manifestation
Inertia	High level of manifestation in economic and technical terms
Adaptability	Low level of manifestation from the economic perspective, high – from the technical viewpoint.

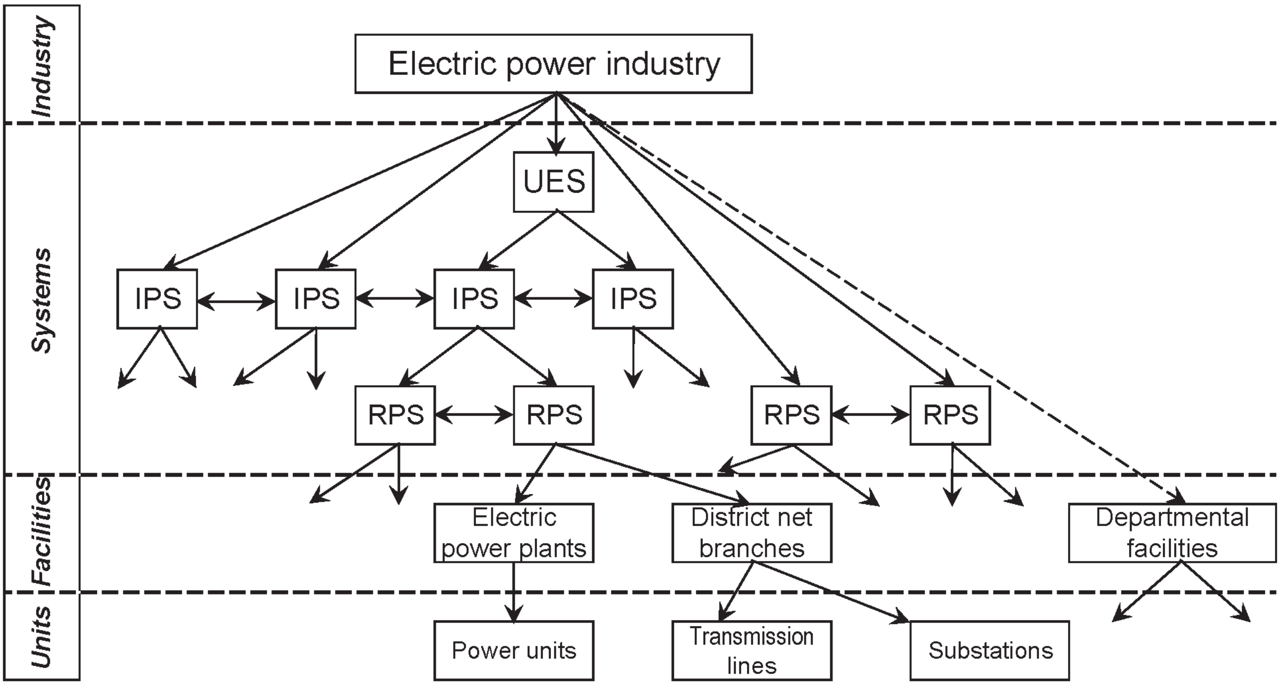


Fig. 3. Territorial and technological hierarchy in the electric power industry of the USSR [7].

explicitly in the specified set of properties). The property of *adaptation* was taken into account when managing the LES expansion and operation. The operational dispatch control of the EPS involved the real-time adjustment of operating conditions and the use of appropriate control and automatic tools. Design and expansion planning of the systems entailed a systematic refinement of plans based on the prevailing conditions.

D. Integrated property of LES reliability

In [6], the of LES authors analyze the property of reliability of power systems, which was previously considered as a main property in the classification by L.A. Melentiev [2]. According to [6], with the development of the electricity industry, more attention must be paid to reliability. This is because the "cost" of accidents is becoming increasingly higher due to the growing unit capacity of generating units and transfer capability of power transmission lines, and accidents can develop in the changing and more complicated operating conditions of energy systems. This property is complex and includes such single features as failure-free operation, maintainability, durability, preservation, stabilability, operational controllability, survivability, and safety [6]. In this case, the range of single properties is wider than that considered earlier and includes, in particular, such new single characteristics as stabilability, i.e., the ability to continuously maintain stability for some time; operation controllability, i.e., the ability to maintain normal operating conditions through control; safety as a property of an object to avoid situations dangerous to people and the environment.

III. The main properties of EPS in a pre-transformation period of centralized control

The characteristics of the main properties of EPS in the set of properties considered in the previous section in the period before the large-scale organizational-technological transformations are summarized in Table 2.

Based on what was stated in the previous section, EPS in the USSR can be characterized as an LES with a high level of system integrity, combined with a low level of autonomy of its subsystems. The territorial and technological hierarchy of the UES of the USSR is shown in Fig. 3 [7].

The high level of system integrity is due to the unity of the operation and expansion goals of the electric power industry and electric power systems of different hierarchical levels, which are aimed at ensuring uninterrupted supply of consumers with electric and thermal energy, and due to the unified (state) ownership of the fixed assets of the electric power industry.

The hierarchy of decisions on the EPS expansion and operation was highly developed and consistently conditioned, and detailed the general decisions made at the upper level into more specific ones at the lower levels of the system's hierarchy. *Uncertainty of information* inevitably existed and affected the general methodology of LES control and, specifically, EPS. The Unified Energy System of the USSR was also distinguished by rather high levels of *cost-effectiveness and reliability*. *Multi-criteria nature* manifested itself in the sense of the possible presence of non-economic criteria (environmental and social) along with economic, as the main one. As for the extended interpretation of multi-criteria nature, i.e., the presence

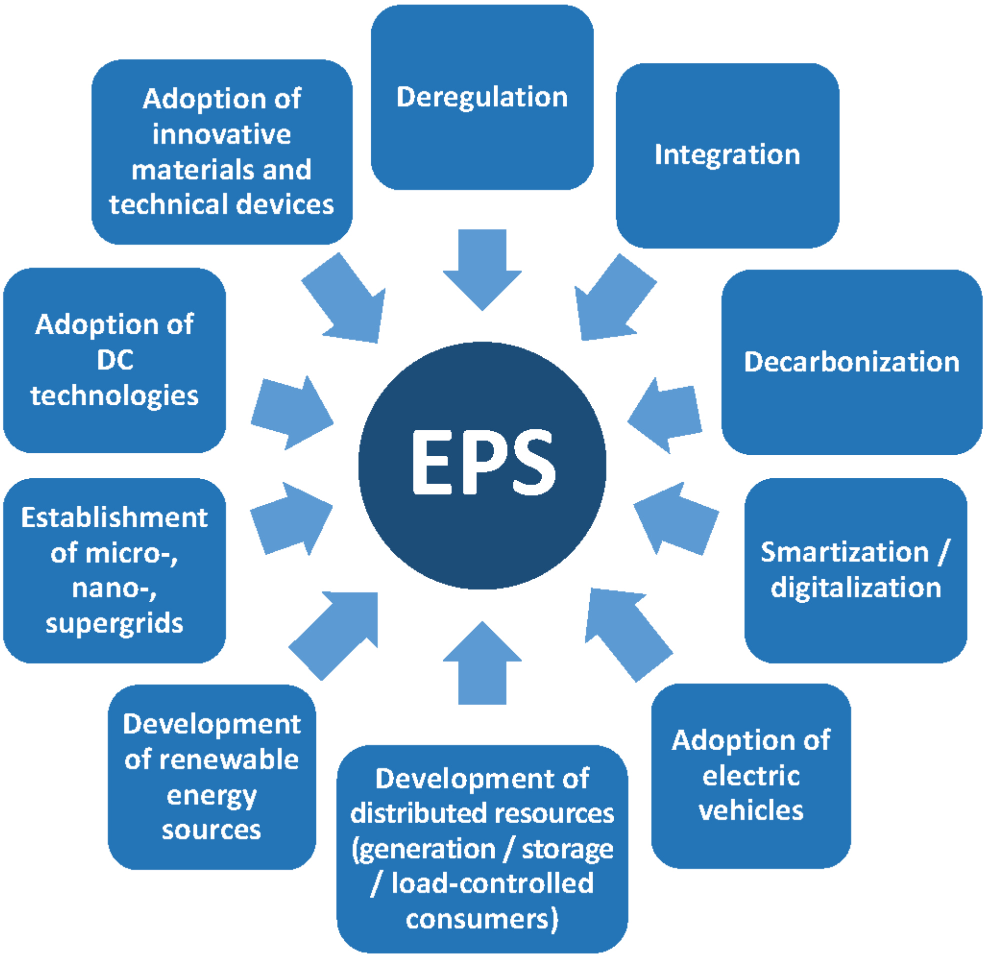


Fig. 4. Trends affecting EPSs and contributing to their transformation.

of the goals for the LES subsystems at different levels of the hierarchy, this property did not manifest itself highly. Subsystems' goals were usually to achieve the overall goal of the entire system. Due to the high concentration of unit production capacities in the energy sector, their high capital intensity, and long construction time, the *system's inertia* was quite high. For these reasons, *the adaptability* of the system (in the economic sense), on the contrary, was rather low. The system *flexibility* associated with adaptability was also low and, although it was not included in the main properties of LES, some authors considered it a significant characteristic of the system. According to [5], adaptation is managed using flexible structures.

Technically, the *inertia* caused by the inertia of the rotating masses of rotors of large synchronous and asynchronous electrical machines was high. However, it is the high inertia in this sense, together with the action of the load-based voltage and frequency regulating effects; the action of the control systems, protection, and emergency control systems; which provided good EPS adaptability to sudden changes in the operating condition and disturbances [8]. In this regard, the flexibility of traditional EPSs (in the technical sense) can be characterized as very high.

Consumers, despite some load regulation programs, incentive tariffs, and others, mainly acted as passive "actors," i.e., as participants having little influence on the processes of production, distribution, and control in the EPS. Therefore, they are not shown in the diagram in Fig. 3.

IV. The main properties of EPS in a pre-transformation period of centralized control

A. Organizational-structural and innovative-technological transformations of EPS

As noted by the former President (2010) of the Institute of Electrical and Electronics Engineers, Power & Energy Society (IEEE PES) V. Raeder, and the IEEE PES President F. Lambert (2020–2021), the electric power industry is transforming, and "everything is changing and changing at the same time" [9].

Different processes/tendencies are taking place in the electric power industry and electric power systems. Some authors identify several most significant processes in current conditions, such as, for example, digitalization, decarbonization, decentralization (3D) [10]. Particular attention is paid to the "energy transition," which implies a transition from the predominant use of gas to the widespread involvement of renewable energy sources in

Table 3. Structure of electrical loads

Superlarge	Large/medium	Small
Megacities, large-scale industrial centers	Large /medium-sized settlements, individual enterprises	Separate small municipal and industrial consumers, including distributed ones
Total electrical load		
Units/tens of GW	Tens/hundreds MW	From several kW to several MW
Energy density		
Up to 1000-2000 W/m^2	50-100 W/m^2	15-20 W/m^2

the energy balance [11]. Apart from the above factors, however, there are many processes and trends that also affect electric power systems and radically change their appearance. These processes/trends are shown in Fig. 4.

These processes/trends are extremely diverse, include organizational-structural transformations and innovative-technological modernization of electric power systems, and differ in duration. The electric power integration, which means the formation of interstate power interconnections with the establishment of interstate electrical connections, has more than a century of history [12]. At the same time, this process continues moving to a new level of formation of transcontinental energy interconnections, and the creation of a Global pool in the distant future. It is worth noting that integration also means the interconnection of energy systems with different energy carriers and the creation of the so-called multi-energy systems, including power, heat, cooling, gas, and other technologically connected

subsystems, which allows converting one type of energy into another [13]. This process is still in the initial stage of development.

As for deregulation, which implies the restructuring, privatization, and liberalization of the electric power industry with the transition from regulated vertically integrated structures to market ones, this process began in the 1980s and is currently continuing in the form of re-reform (adjustment of the originally formed structures that did not ensure the efficient operation of the market). Russia started an active phase of reforming the electric power industry at the beginning of the 2000s. Electricity and capacity markets were created, but this process has not finished yet. At the same time, there are significantly different views on the reform implications, including their negative assessment [14]. The deregulation process has radically changed the structural organization and some basic properties of the electric power industry, which will be discussed below.

The decarbonization process is global in nature [15], and the development of renewable energy sources (both distributed and centralized) is a measure to reduce carbon emissions and overcome global warming.

The development trend of distributed energy resources, including energy generation, energy storage, and load-controlled consumers, has become extremely large-scale. It is even opposed to the development of "centralized" energy sources and energy systems, and the question is raised how far this process will go and whether "centralized" energy systems will remain at all [16]. This issue is discussed further.

The development of distributed energy resources is closely related to the establishment of microsystems (mini-, nano-systems) [17] and the adoption of electric vehicles. Lower-level systems (micro-, nano-, mini-) become crucial active EPS components exchanging energy with each other through horizontal connections and supplying its surplus to a "centralized" system. Since many modern electrical loads operate on direct current, it becomes expedient for the power systems of the lower hierarchy level to operate on direct current or to create hybrid AC/DC systems [8].

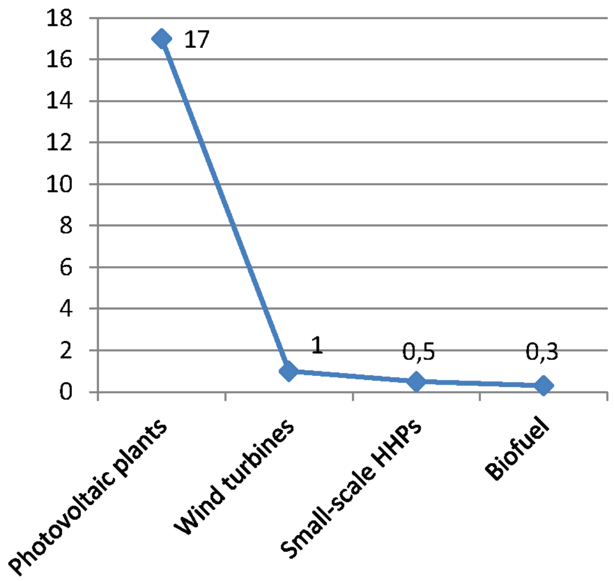
The process of introducing direct current into modern EPSs is not limited only to micro- (nano-, mini-) systems. DC lines are widely used to transport large amounts of electricity over long distances; DC links are employed for asynchronous connections of power systems, including those having different frequencies of alternating current.

Innovative materials and devices, smartization and digitalization tools, when used in energy systems and their control systems, turn modern EPSs into complex cyber-physical systems [18], which also changes their basic properties.

B. "Centralized" EPS and distributed generation

The question is often raised about how far the processes of distributed sources expansion and electrical load control can go, as they reduce the role of large "centralized" power plants in EPS and lead to their "decentralization." As a result, the level of the integrity of EPSs will continue to decrease, while the level of autonomy of their subsystems will increase. There are some factors, however, which impede the complete "decentralization" of EPSs and maintain their structure as a combined centralized-distributed one. These are the structure and density of electrical loads, the energy density of generating sources, economies of scale, and terms of project financing.

According to the structure, electrical loads are



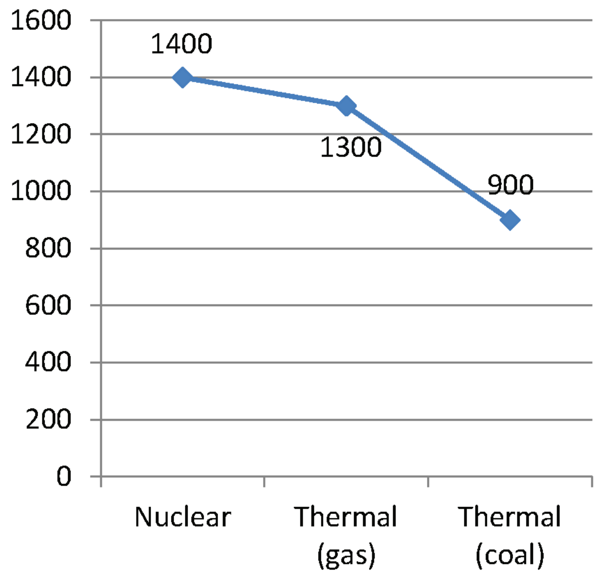


Fig. 5. The energy density of generating sources, W/m²: a) unconventional (renewable) energy sources [16]; b) conventional energy sources (calculated based on the data from [19]).

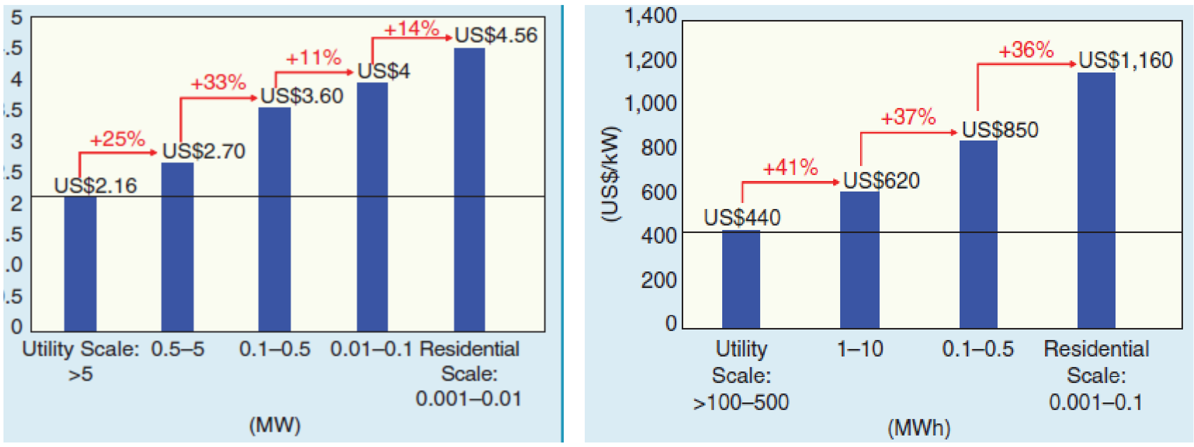


Fig. 6. Economies of scale in electricity generation and storage [21]: a) photovoltaic converters; b) lithium-ion storage systems.

divided into super-large, large, medium, and small (see Table 3). The first ones, which include large-scale urban agglomerations and industrial centers, are gigawatt loads, the second and third (individual urban settlements and industrial enterprises) are megawatt loads, and, finally, small ones (individual municipal and industrial consumers) are loads of kilowatt class. According to [16], the electrical load of the first of the listed groups of consumers cannot be covered only by distributed, primarily renewable, generation, it requires large centralized energy sources.

This point is confirmed by the data presented in Fig. 5. Comparison of the energy density of renewable energy sources with the energy density of consumers of the first group (Table 3 and Fig. 5a) shows that distributed sources of renewable energy sources alone cannot cover the demand of the specified group of consumers.

As for such distributed generation resources as microturbines, gas reciprocating plants, and other mini-TPPs [20, and others], which have an energy density comparable to consumers of the first group, their placement in the electrical load centers, which are already considerably affected by transport, residential, industrial and other essential infrastructures, can be constrained by socio-ecological factors (emissions of harmful substances, thermal pollution, noise, unacceptable appearance, and others) and limited possibilities of organizing fuel supply (under the conditions of many existing connections, including pipeline and information-communication ones).

In connection with the above, power supply to consumers of the first group requires the use of large “centralized” power plants located outside these load centers and the electricity transport through powerful

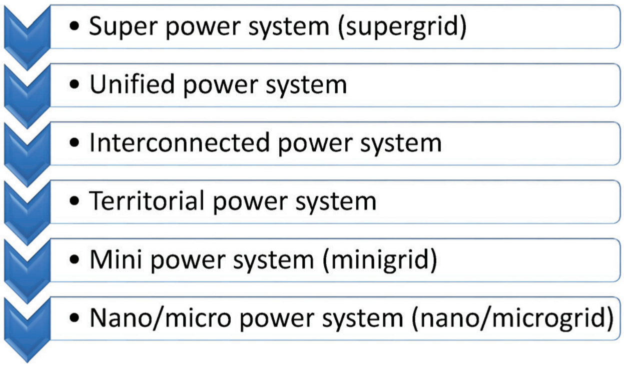


Fig. 7. Territorial and technological hierarchy of EPSs under transformation.

power lines. It is worth noting that the energy density of such sources corresponds to the energy density of consumers of the first group (see Fig. 5b).

According to modern research, the electricity generation sector enjoys economies of scale, including those for solar and storage plants with a modular principle of capacity expansion, i.e., large plants of this kind, operating in an EPS, are more cost-effective than small ones operating at the consumer. Therefore, depending on the specific conditions (a developed power grid infrastructure, economic indicators, and others), large centralized sources and distributed generation plants (including those based on renewable energy sources) also expand. According to the estimates [21] (Fig. 6), switching from small distributed generation sources and storage facilities to large "centralized" plants reduces specific capital investments by more than 2 times.

Another factor in favor of keeping "centralized" energy systems in some form is that "centralized" generation projects implemented by large energy companies are usually funded by banks on more favorable terms than small distributed generation projects [22], which reduces the economic efficiency of distributed generation plants. The state's support to distributed generation projects under concessional lending programs, however, will increase their economic attractiveness.

Thus, still, there are conditions under which it is expedient to develop large centralized energy sources and systems, as well as their interconnections, which continue to play a crucial role in the energy supply of consumers. Although the active development of distributed generation is also ongoing

C. Transformation of EPS properties

In the context of the transformation of EPSs, their hierarchy becomes more complicated. Instead of the traditional two-level territorial-technological hierarchy of energy systems (Unified system - Territorial system) for small countries and EPS, or three-level hierarchy (Unified system – Interconnected system - Territorial system) for large countries (Russia, China, the USA) and EPSs, there emerges a six-level hierarchy, which at the upper level covers interstate power interconnections and at the lower level additionally includes mini- and micro-systems (Fig. 7). As a result, the property of the *hierarchy*

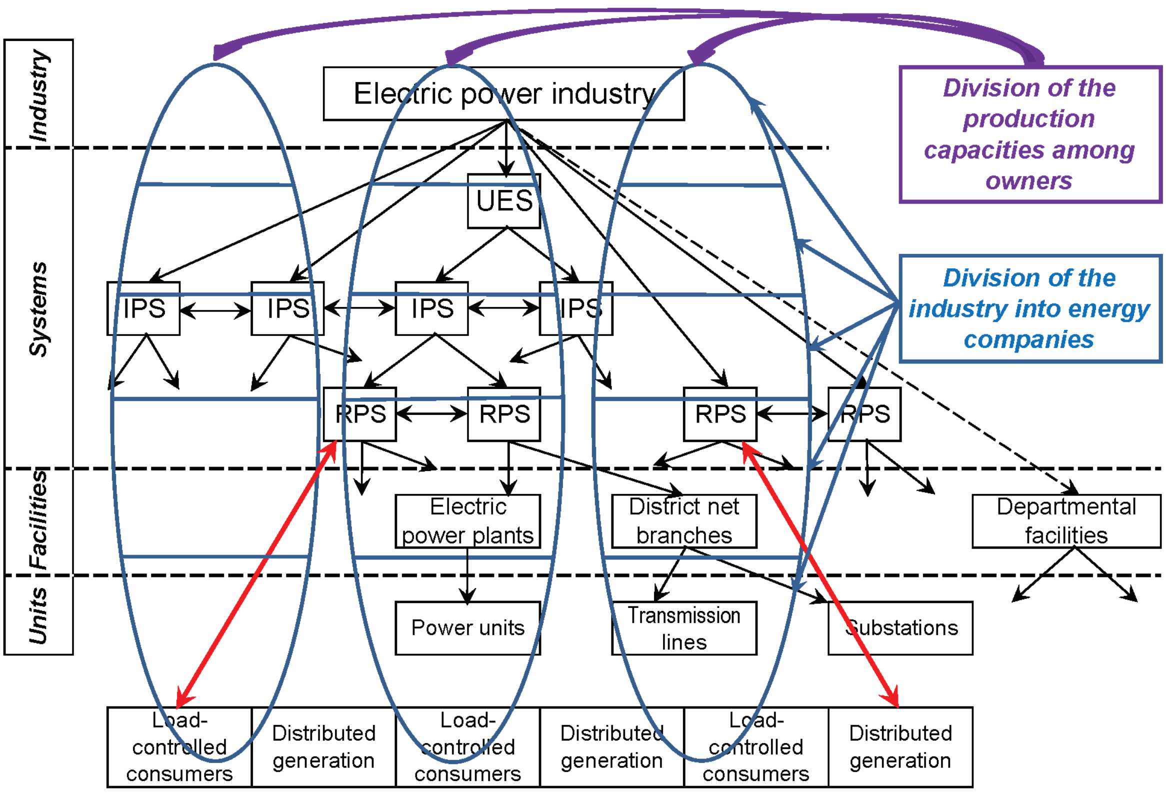


Fig. 8. Organizational-structural transformation of the electric power industry.

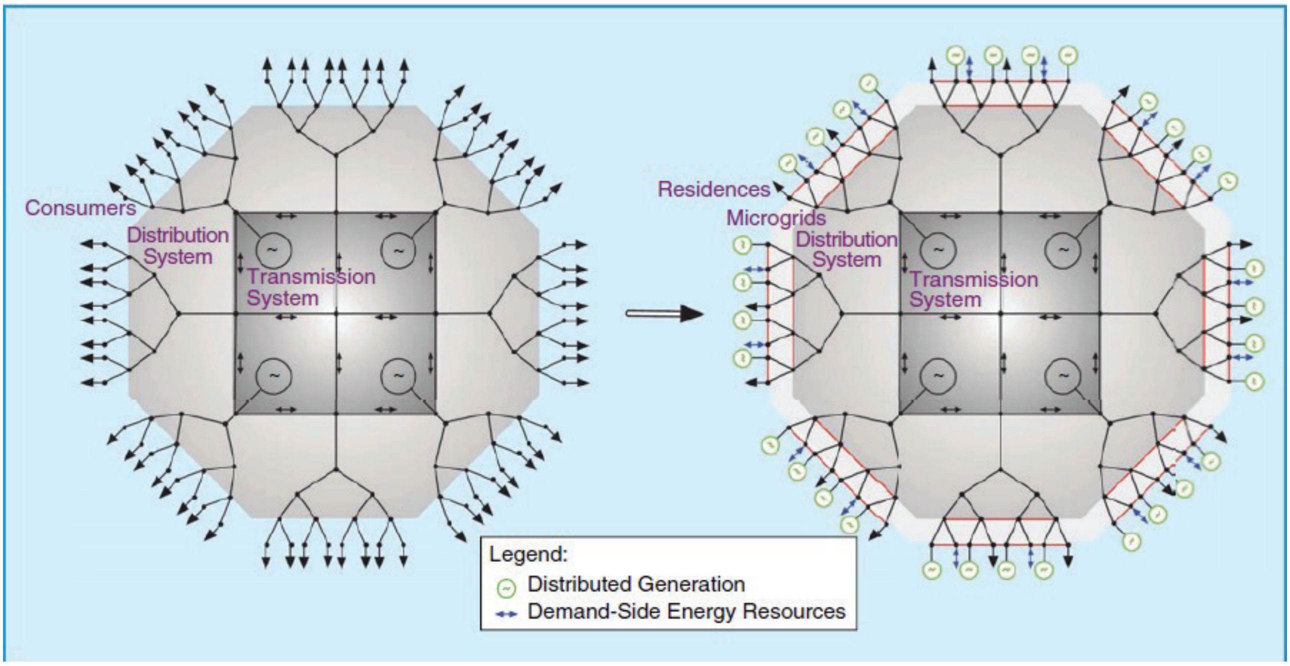


Fig. 9. Centralized-distributed cyber-physical electric power system [25].

of decisions significantly expands. Moreover, at the lower levels of micro-and mini-systems, the horizontal coordination of decisions is enhanced.

Privatization and restructuring resulted in the division of production assets in the Russian electric power industry between various owners, including foreign ones (energy companies from Germany, Italy, Finland). The state (the Russian Federation) also remained one of the owners, but to a different extent in different companies. New LES subsystems were created, i.e., energy companies owned by different owners, as well as electricity and capacity markets, within which these energy companies operate. Energy companies and their owners have their objective functions of efficiency that determine their behavior in the process of operation and expansion. In addition, new "actors" have appeared, i.e., load-controlled consumers, prosumers (producers-consumers), and distributed generating plants, which have become active participants in the electric power markets as a result of the electric power industry reform (Fig. 8). Thus, in terms of organizational and structural aspects, the level of the *autonomy* of subsystems (energy companies and consumers) has increased, and the level of *integrity* of the entire system, on the contrary, has decreased.

Since, as noted above, the reform results in the emergence of many new entities with their goals and interests, given the extended interpretation of the property of the *multi-criteria nature* [1], this leads to an increase in the level of this property. In addition, initially, when assessing the efficiency of the energy system's operation and expansion, the property of multi-criteria nature implied considering not only economic criteria but also non-economic, including environmental ones. Given the global trends in the development of renewable energy sources and the greening of energy production, Russia's ratification of the Paris Climate Agreement, and the country's transition to a low-carbon development path [15, 23, 24], the significance of considering environmental criteria when justifying and making decisions in the field of energy increases dramatically. Moreover, the importance of these criteria becomes commensurate with that of economic criteria. Thus, the level of the multi-criteria nature rises further.

Finally, with the growing number of entities in the electric power industry, one can expect an increase in the *uncertainty of information* about the future conditions for the EPS operation and expansion. With the emergence of load-controlled consumers and distributed generation, the uncertainty of prospective demand for electricity and capacity increases when justifying and making decisions on the expansion of large "centralized" energy sources and power transmission lines. Current demand will also be more uncertain since it will be formed under the influence of a larger number of uncertain factors, including, apart from the traditional demand of electricity consumers, also the consumption/generation of many prosumers, stochastic generation of renewable energy sources, both centralized and distributed ones. On the other hand, the uncertainty is likely to be minimal for distributed plants/prosumers themselves, since they will work according to their schedule, supplying surplus to the network, or, conversely, receiving energy from the network, if necessary, thus "shifting" their uncertainty to the "centralized" system.

In the context of transformation, the development of distributed generation within the "centralized" EPS (see above) leads to the establishment of a centralized-distributed electric power system, and this system becomes a cyber-physical one, which, based on the digitalization, integrates technological, control and market systems, as well as all stakeholders involved, i.e., business, consumers, and prosumers [18]. As noted in [25], the centrally-distributed cyber-physical (CD CP) EPS (Fig. 9) represents a compelling vision of future electric power systems that are formed through the convergence of trends, forces, and policies. CD CP EPSs include thousands of local distribution areas/networks managed (controlled) by Distribution System Operators (DSOs) connected to large/"centralized" EPS for electricity trading in/exchanging with the wholesale market and providing ancillary services. The final state of the CD CP EPS has not yet been studied in detail, the motion towards it from the current state occurs at various rates in different countries and regions of the world, and the transition can be chaotic.

The transformation of energy systems and their change into CD CP EPS will undoubtedly affect their properties. As noted above, many entities operate within the CD CP EPS, including distributed small generating plants and prosumers. These power plants have low capital costs, short construction periods, and, accordingly, the possibility of a rapid increase in capacity, which reduces the *inertia* of the system (economically), enhances its adaptability to changing uncertain conditions (for example, changes in the electricity demand), and makes it more *flexible* in an economic sense.

These properties also have a technical interpretation. In contrast to traditional units of "centralized" power plants, the rotors of small generators of distributed plants have a reduced inertia constant and simplified control systems [26]. This and the active use of innovative technologies based on power electronics in electricity production, transport, distribution, storage, and consumption considerably reduce the load-based regulating frequency and voltage effects, and the inertial capabilities of the EPS, and, as a consequence, the levels of the system adaptability and flexibility go down (in a technical sense) either. Moreover, an increasing share of randomly fluctuating generation based on renewable energy resources leads to a further decrease in the EPS flexibility [27]. However, advanced highly-efficient control systems can provide a dramatic increase in the controllability and flexibility of EPS [8, 28].

Changes in the properties of EPSs due to their transformation manifest themselves in operation, expansion, and the market organization of these systems.

The property of reliability in the basic set of properties of LESs is associated with their operation [1]. In the context of EPS transformation, this property undergoes changes that affect its features, such as stability, survivability, and others [29, 30]. As the EPS transforms, "voltage" stability, "frequency" stability, and thermal stability, which previously were local, come to the fore, although the stability that prevailed in the traditional EPS was "angle" stability. Stability losses are closely intertwined and are complexly connected by cause-and-effect relationships with each other and phenomena (events) in the EPS. Any of the above-mentioned phenomena can spread in one form or another to other parts of the EPS and finally to the entire power system and evolve into a system accident [29]. On the other hand, the distributed generation plants on the low voltage side of consumers, on the contrary, have a positive effect on the level of reliability of power supply to consumers since if a high voltage supply substation fails, these plants at least allow reducing (or eliminating) the electricity shortage for consumers [26].

As stated above, structurally and organizationally, the EPS integrity decreases, while the autonomy, on the contrary, increases. It is important to scrutinize this issue from the "technical" viewpoint, to be more precise, from the perspective of operational dispatch control. The system of operational dispatch control of the EPS is improved to reflect the ongoing transformations, especially given the involvement of consumers and the spread of distributed generation. Load-controlled consumers and, to an even greater extent, prosumers increase the uncertainties in dispatching control of EPSs due to the independent control of their electric loads and small generating plants [31]. Therefore, in addition to network and system operators, it is advisable to create "aggregators of distributed energy resources" and "distribution operators" to ensure participation of consumers in the EPS control, which complicates the dispatch control system and increases the hierarchy of dispatch decisions. Thus, the strengthening of the autonomy and the weakening of the integrity of the transformed EPS extend to the dispatch control system, thereby increasing the role of lower levels of the control system hierarchy (load and prosumers) and strengthening the horizontal connections between these hierarchical levels, and also manifest themselves in the operation of the entire EPS.

A decrease in the integrity of the system and an increase in the autonomy of its subsystems, as a result of restructuring and privatization of the industry; the formation of many independent energy companies, load-controlled consumers, and prosumers with their economic interests and objective functions of efficiency; and due to the growing hierarchy of decisions through the creation of additional hierarchy levels (micro-, mini-systems at the lower level and super-systems at the upper level) are also observed for the aspect of EPS expansion. These factors increase the uncertainty of the future EPS expansion conditions and complicate the process of this expansion. Therefore, it is necessary to create a management system for the electric power industry development, within which the many interests of the entities involved at all levels of the territorial and technological hierarchy of the EPS are coordinated, and provide further advancement of the methodology for planning the development of the electric power industry, power systems, and power companies in the context of their transformation.

Table 4. Transformation of EPS properties in a changing environment

Property	Transformation
System integrity	Declines in organizational, technical, and control terms
Subsystem autonomy	Grows in organizational, technical, and control terms
Hierarchy of decisions	Expands
Incomplete information	Expands
Cost-effectiveness	↙ ↗
Reliability	↙ ↗
Dynamics	Persists
Multi-criteria nature	Expands
Inertia	Declines economically and technically
Adaptability	Rises economically and declines technically

The expansion of microsystems and the involvement of consumers and prosumers cause the transformation of the electricity and capacity markets. They become structurally more complicated, with the number of their participants rising dramatically, which raises the uncertainty, increases the hierarchy of decisions, enhances the autonomy, and decreases the integrity of the structural organization of the electric power industry. The cost-effectiveness of the electric power industry in a market environment is assessed ambiguously. On the one hand, the competition is believed to force market participants to reduce their costs "in the fight" for the consumer; on the other hand, the real markets are imperfect, which allows companies to overcharge equilibrium prices and generate excess profits.

Table 4 summarizes the analysis of EPS properties brought about by their structural-organizational and innovative-technological transformations.

The *integrity* of the systems decreases in organizational, technical, and control terms. *Autonomy* of the subsystems in all these respects, however, on the contrary, increases. *The properties of the hierarchy of decisions* and the *incompleteness of information* expand. The change in the level of the system *cost-effectiveness* property is not obvious because, as noted, it is affected by two oppositely directed vectors: competition in the electricity markets, on the one hand, leads to a decrease in prices, on the other hand, in the imperfect markets, it can also lead to their growth. Change in the level of the reliability property is not apparent either. Dynamics of systems, as can be estimated, is preserved, and the property of *multi-criteria nature* expands due to the emerging multitude of new EPS entities with their interests and goals. The *inertia* of systems decreases both in the economic and technical sense. However, whereas in the economic sense, this has a positive result, in the technical sense (i.e., in the sense of reducing the ability to "extinguish" internal and external destabilizing factors in the system), it is rather negative. As a result, this decreases the level of another property, i.e., *adaptability* and the related *flexibility* of the system. The decrease in the inertia of systems causes adaptability to grow in the economic sense.

V General lines for further research

The change in the EPS properties, which, as noted, in the context of transformation does not always have a positive direction, will require various compensating measures and means. These are the improvement in control systems, the development of energy storage devices, intelligent FACTS devices, automatic reconfiguration of the electrical network [8], and others. First of all, however, it is necessary to conduct a whole host of scientific research in this area. These studies will follow the requirements for the methodology and modeling of EPS in a new environment and rely on the above analysis of the transformation of EPS properties.

Firstly, a decline in the level of the system integrity and, accordingly, an increase in the level of subsystem autonomy, as well as the expansion of multi-criteria nature, require the consideration of the organizational unbundling of the EPS with a cardinal widening of the set of decision-makers, and, accordingly, the need to use equilibrium, multi-agent and two-level modeling in problems of operation, expansion and structural organization of the electric power industry. Secondly, the expansion of the property of the hierarchy of decisions presupposes the studies to be conducted for the hierarchical levels of mini- (micro-) and super-systems, and the use of two-level modeling to study centralized – distributed EPSs integrating large "centralized" systems at the upper hierarchical level, and micro-and mini-systems, as well as individual consumers prosumers at the lower level. Thirdly, the growing incompleteness of information leads to the need to develop new approaches and models

Table 5. General directions of research due to changes in the EPS properties

Architecture and properties
Micro, mini, super systems
Two-level (centralized system – distributed resources) models of EPS operation, expansion, and structural organization
Expansion and operation of control systems with vertical horizontal coordination of centralized generation and distributed energy resources
Consideration of the high uncertainty of “clean” power consumption in real-time control and long-term development
Conceptual and methodological studies and modeling of multi-level markets, including many participants
Equilibrium models of operation and expansion in terms of structural organization of the EPS
Mathematical models of expansion and operation based on multi-criteria optimization
Electric power applications of the Internet of Things, blockchain, big data, artificial intelligence

to factor in the extended range of information uncertainty in the process of expansion and operation of EPSs and their control. Fourthly, as noted, changes in the properties of cost-effectiveness and reliability in the context of EPS transformation are ambiguous and, therefore, require research of market structures that affect the property of cost-effectiveness (as well as the reliability of microsystems), load-controlled consumers, prosumers, and the impact, along with the reliability of large “centralized” systems, on the reliability of power supply to consumers in general. Fifthly, the increasing significance of environmental factors, primarily due to the problem of global climate change coming to the fore, and the need to reduce carbon dioxide emissions today require the development of appropriate mathematical models, including those using multi-objective optimization. Sixthly, in a new context, the decline in the levels of EPS inertia, adaptability, and flexibility in the technical sense requires compensation for the negative consequences of this decline and appropriate research and development of highly-effective protection, automation, and control systems.

General directions of research, due to the transformation of the main properties of EPS in the new context, are presented in Table 5. In this case, they are not divided into specific problems, but such a division was made in the studies, which are currently underway at the Energy Systems Institute of Siberian Branch of the Russian Academy of Sciences.

These studies include those focusing on the properties of flexibility, stability, survivability, and vulnerability of EPS [30, 32]; dealing with the creation of intelligent multi-agent hierarchical systems of operational dispatch control of cyber-physical centralized-distributed EPS [17], equilibrium modeling of the EPS expansion given their structural organization [33]; addressing mini- and super-systems/grids [17, 34], expansion management system [35] and a further improvement in the methodology for planning the development of the electric power industry in the context of EPS transformation [36]. The in-depth studies are also conducted to investigate the transformation of properties and examine new properties, which are expected to arise in the process of future EPS formation. Finally, it is necessary to develop applications to the considered subject domain of the Internet of things, blockchain, artificial intelligence, and digital twins and carry out a variety of other scientific studies.

VI. Conclusion

In the context of current and expected transformations, electric power systems are becoming even more complex in terms of structure, technology, and control, and their behavior and conditions of existence are getting less predictable. Control systems of such complex centralized-distributed cyber-physical systems are becoming increasingly “smartized,” and acquire, albeit to a limited extent, the ability to make decisions. Thus, the emergence of new properties characterizing the expanded capabilities of future EPSs is real, which will require their conceptual interpretation from various perspectives, and comprehension.

Further scrutiny is necessary to create and improve scientific, methodological, and model tools, which will ensure efficient and reliable operation, expansion, and structural organization of centrally-distributed cyber-physical systems, given the transformation of their properties.

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Principles of Constructing Artificial Intelligence Systems and their Application in Electrical Power Industry

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***Abstract* — The paper considers two historically established directions of building artificial intelligence systems: expert systems and neural networks. The consideration is given to parallels and analogies between the work of neural networks and the work of the human brain, the hierarchical structure of the brain, the history of the neurocybernetics development, and the theoretical foundations of neural networks.**

Models of reasoning of specialists are used in expert systems based on production rules (expressions of the form "if ..., then"). The main semantic elements in neural networks are models of neurons and layers of neurons (input, output, intermediate). Large amounts of data are associated with neuron models (the so-called "big data").

The paper gives examples of using neural networks and artificial intelligence systems in the electric power industry for the electrical equipment state monitoring, operational dispatch control of electrical networks, for the analysis of emergencies, and intelligent functions of automated dispatch control systems (ADCS).

***Index Terms*: artificial intelligence systems, expert systems, neural networks, hierarchical structure of the brain, neurocybernetics, electrical equipment state monitoring, operational dispatch control of power grids, emergencies, automated dispatch control systems (ADCS).**

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I. Introduction. Problem statement

Once, many years ago, Descartes, looking through a barred window at a growing oak in the courtyard, realized that with the help of a window lattice it was possible to specify the positions of parts of an oak (trunk, branches, leaves) by numbers, i.e., to digitize an oak! By reducing the mesh size of the lattice, which will have more and more details, one can digitize an oak. Descartes exclaimed: "Eureka!" and created a rectangular cartesian coordinate system. This was the moment of paramount importance in the mathematization of physics and the beginning of digitalization. Any material object could be encoded using Cartesian coordinates. The motion of this object could be described by functional transformations of Cartesian coordinates. We can say that a numerical image of physical space was created. Today's digitalization began with that very event.

This paper discusses two historically established directions of building artificial intelligence systems [1–3]:

expert systems,

neural networks.

Neural networks and expert systems are a large class of systems, and their architecture is analogous to the construction of neural tissue from neurons. One of the most common architectures, a multilayer perceptron with error backpropagation, simulates the operation of neurons as part of a hierarchical network, where each higher-level neuron is connected by its inputs to the outputs of neurons of the underlying layer [1].

Logical and symbolic operational disciplines have dominated artificial neural networks in recent years. For example, expert systems have been widely promoted and have notable success, as well as failures. Some scientists state that artificial neural networks will replace modern artificial intelligence, but there is much evidence that they will combine into systems, where each approach is used to solve the problems it copes with better [2].

This view is reinforced by the way people function in the world. Pattern recognition is responsible for the activity that requires a quick response. Since actions are performed quickly and unconsciously, this mode of functioning is critical for survival in a hostile environment. Imagine just what would happen if our ancestors were forced to consider their reaction to a jumping predator?

When our pattern recognition system is unable to give an adequate interpretation, the question is transmitted to the higher parts of the brain. They may ask for more information and take longer, but the quality of the resulting solutions may be higher.

The values of the input parameters are fed to the neurons of the lowest layer, which is why it is necessary to make some decisions, predict the development of the situation, etc. These values are considered signals transmitted to the next layer, weakening or amplifying depending on the numerical values (weights) attributed to interneuronal connections. As a result, some value is generated at the neuron output of the uppermost layer, which is considered a response, i.e., reaction of the entire network to the entered values of the input parameters.

For the network to be used in the future, it must first be "trained" on the data obtained earlier, for which both values of input parameters and correct answers to them are known. Training involves selecting the weights of interneuronal connections that ensure the closest proximity of the network responses to the known correct answers [1–5].

The object of the scientific research of this paper is to review and investigate the development of artificial intelligence (AI) systems in the electric power industry. As noted in the Analytical Review prepared by the Russian Energy Agency of the Ministry of Energy of Russia in terms of the frequency of references in various publications around the world, the functional AI applications are divided into nine main groups:

1. Methods of management (growth + 55% over the last 4 years);
2. "Machine vision" (growth by 49%);
3. "Distributed intelligence;"
4. Natural Language Processing (+ 33% growth);
5. Representation of knowledge and logical judgments;
6. Planned behavior (growth + 37%);
7. Predictive (predictive) analytics;
8. Robotization (growth + 55%);
9. Processing of speech information (+ 15% growth).

The most active use of artificial intelligence applications was recorded in the following groups:

- Transport (15% of all patents, + 30% growth);
- Telecommunications (15% of all patents, + 24% growth);
- Biology and medical research (12% of all patents).

Agriculture (+ 30%) and settlement of government tasks (+ 30%) are also rapidly growing application areas.

Energy tasks are separated into a separate area of use (energy management).

Examples of the artificial intelligence methods used in energy are listed in [6]. The most promising task groups, where AI can have an effect, are:

- forecasting tasks (meteorological information, equipment operation status, energy consumption changes, etc.);
- optimization tasks (operating conditions of power system components, consumption, network configuration, etc.);
- management tasks (artificial lighting, renewable energy sources, batteries, asset performance, etc.);
- communication tasks (energy companies with consumers);
- the tasks of developing services and services (in terms of customer satisfaction with the range of services provided by companies, participation of enterprises in the energy markets, solving issues of quality assurance).
- It is noted that the expansion of the use of artificial intelligence tools in the energy sector will inevitably occur along with such processes as:
- energy transformation due to the expansion of the use of local renewable energy sources, as well as the smartization of energy generation,
- transmission, and consumption (smart technology);
- digital transformation due to the growing needs of monitoring and data analysis ("big data") and the introduction of new technologies (for example, blockchain, "digital substation," unmanned devices for monitoring objects, etc.);
- unification and mutual influence of various energy sectors and transport sectors (for example, Power-to-X technology) [6].

Thus, the main focus of this paper is on the principles of building artificial intelligence systems and their application in the electric power industry.

This paper has the following structure: introduction; parallels and analogies between the work of neural networks and the work of the human brain; the hierarchical structure of the brain and modeling of thinking processes in p-adic coordinate systems; general principles of constructing artificial intelligence systems and their application in the electric power industry.

II. Parallels and analogies with the work of the human brain

Neural networks are designed similar to the human nervous system, but they use statistical analysis to recognize patterns from a large amount of information through adaptive learning. The nervous system and the human brain are composed of neurons connected by nerve fibers. Nerve fibers are capable of transmitting electrical impulses between neurons. Processes of transmitting irritations from our skin, ears, and eyes to the brain; processes of thinking and controlling actions – all of them are implemented in a

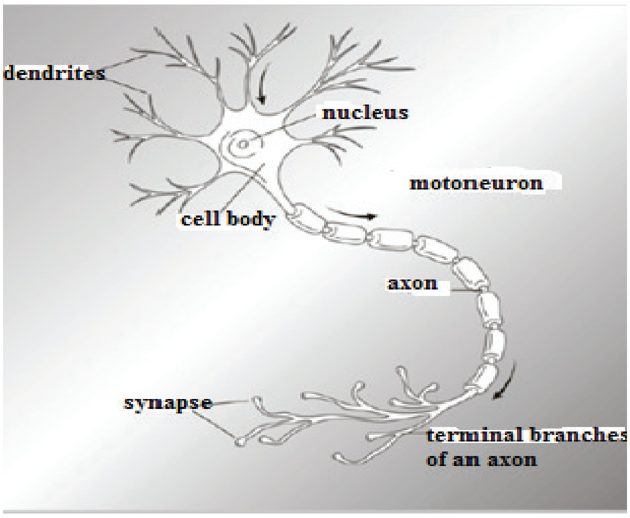

Fig. 1. Neuron diagram. Electrical signals travel along the neural axon to reach the synapse. Neurotransmitters regulate the passage of electrical signals through synapses.

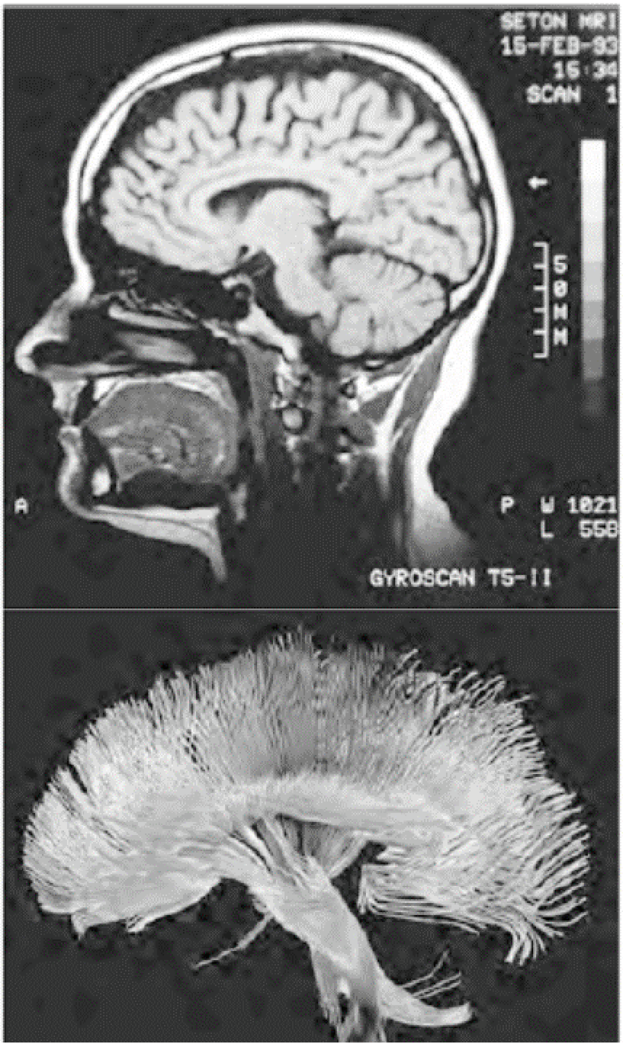

Fig. 2. A functional MRI image showing areas of high mental activity. The lower image shows a flower-like structure created by a diffusion MRI machine tracking neural pathways and brain connections.

living organism as transfer of electrical impulses between neurons.

Each neuron has two types of nerve fibers – dendrites, along which impulses are received, and a single axon, along which the neuron can transmit impulses. Axon contacts the dendrites of other neurons through special structures, synapses, which affect the impulse strength (Fig. 1) [3–5].

Artificial intelligence systems and expert systems are too "fragile," as these systems encounter a situation not envisaged by the developer, they either form error messages or give incorrect results. In other words, these programs can be quite easily "confused." They cannot continuously self-learn, as a human does while solving emerging problems.

In the mid-1980s, many researchers recommended using neural networks to overcome these (and other) disadvantages.

A neural network, in its most simplified form, can be considered as a way of modeling the principles of organization and functioning mechanisms of the human brain in technical systems. Modern concepts suggest that the human cerebral cortex is a set of elementary interconnected cells (neurons), the number of which is estimated at 10^{10}. Technical systems, in which an attempt is made to reproduce such a structure (hardware or software), albeit on a limited scale, are called neural networks.

A neuron in the brain receives input signals from many other neurons, and the signals have a form of electrical impulses. Neuron inputs are divided into two categories – excitatory and inhibitory. The signal received at the excitatory input increases the neuron excitability, which, when a certain threshold is reached, leads to the formation of an impulse at the output. The signal arriving at the inhibitory input, on the contrary, reduces the excitability of the neuron. Each neuron is characterized by an internal state and a threshold of excitability. If the sum of signals at the excitatory and inhibitory inputs of the neuron exceeds this threshold, the neuron generates an output signal that goes to inputs of other neurons connected to it, i.e., there is a propagation of excitation through the neural network. There are at least 30 billion neurons in the brain, and each of them can have up to 10 thousand connections with other neurons.

The switching time of an individual neuron in the brain is of the order of a few milliseconds, i.e., the switching process is slow. Therefore, the researchers concluded that the high performance of information processing in the human brain can only be explained by the parallel operation of many relatively slow neurons and a large number of mutual connections between them. This explains the widespread use of the term "massive parallelism" in the literature on neural networks [1–5].

To create a model of the work of the human brain, then to move on to the creation of an artificial intelligence system, one can try to use the same coordinate system to describe the mental world that was used to describe the material world. The overwhelming majority of researchers follow this path. Hundreds of laboratories worldwide use more and more sophisticated magnetic resonance devices to make Cartesian card activation of neurons in the brain increasingly more accurate. This is an interesting activity. There are doubts, however, that it can lead to understanding the mental processes and the work of the brain. Recently, numerous studies have also been conducted to create quantum models of the brain. This direction is right. Making sure that the processes occur in the human brain, it is impossible to put it in a system of coordinates of the Euclidean space R^3, it is necessary to try to put it in other multi-dimensional spaces, for example, Hilbert space H. However, the vast majority of quantum mental studies are based on an extremely questionable reduction postulate: the mental processes in the brain can be reduced to quantum physical processes in the microworld (Fig. 2) [7–9].

The quantum behavior of the brain is a consequence of its specific informational structure and not the effect of the quantum behavior of microscopic components of the human brain.

Therefore, on the way to artificial intelligence systems, we must create a mathematical model of the mental space, and choose the appropriate coordinate system.

The most important feature of the real continuum is its homogeneity. All points of physical space (with a three-dimensional model R^3) are equal. We cannot say that one point is more important than another. However, brain activity is inhomogeneous. We cannot say that all human thoughts, ideas, concepts, feelings are equal. Moreover, the brain is hierarchical. There is a clearly expressed hierarchy of concepts, images, and feelings. However, there is no complete orderliness in the mental space. It is impossible to hierarchically arrange all concepts, images, and feelings. There are non-comparable ("incommensurable") spiritual objects, thoughts, and images [7].

III. History of the issue

The theoretical foundations of neural networks were laid back in the 1940s by W. McCulloch and W. Pitts. In 1943, their work "The Logical Calculus of Ideas Relating to Nervous Activity" was published, in which authors built a model of a neuron and formulated the principles of constructing artificial neural networks.

A substantial impetus to the development of neurocybernetics was given by the American neurophysiologist Frank Rosenblatt, who in 1962 proposed his neural network model – the perceptron. Initially, it was received with great enthusiasm, but soon it came under intense attack from major scientific authorities. And although a detailed analysis of their arguments shows that they did not contest exactly the perceptron proposed by Rosenblatt, large research on neural networks has been curtailed for almost ten years.

Despite this, the 70 years saw a lot of interesting developments, such as cognition capable of recognizing fairly complex images well regardless of rotation and zoom.

In 1982, the American biophysicist J. Hopfield proposed an original neural network model named after him. Many efficient algorithms were found (a counter-flow network, bidirectional associative memory, and others) in the next few years.

In 1986, J. Hinton and his colleagues published an article describing a neural network model and an algorithm for its training, which gave a new impetus to research on artificial neural networks.

The next book, "Modeling thinking processes in *p*-adic coordinate systems," deals with the mathematical modeling of thinking processes based on dynamic systems on *p*-adic trees and more general ultrametric mental spaces. Applications in psychology (including Freud's psychoanalysis) and cognitive sciences are considered in [7].

IV. Hierarchical structure of the brain

In modern neurophysiological and cognitive literature, one can gradually become stuck in R^3-map scintillation excited neurons, neural networks work, electricity flows in the brain, i.e., be automatically involved in using mentality's real processes of the Cartesian coordinate system (developed to investigate Matter) for research. However, Sigmund Freud did not write about the functioning of neural systems. He described streams of ideas, representations, and desires, and these mental objects in the Freudian description are no less real than material objects. Mental objects evolve, interact with each other; mental forces are active here. For example, one of these forces displaces strong (often shock) but forbidden experiences into the unconscious, thereby creating complexes. The complexes, in turn, induce forces acting from the subconscious on the streams of conscious ideas.

Intuitively, it is clear that we are dealing with dynamics in mental space, very similar to the dynamics of material objects in physical space. It is only necessary to introduce an appropriate system of mental coordinates and describe the mental flows mathematically. For reasons that have already been given above, there is no capability to use models. As noted, mental space is not homogeneous; it is also not ordered: we cannot compare two arbitrary mental objects. On the other hand, there is a clear hierarchical structure in the mental world. Note that disorder is quite consistent with hierarchy. For two mental objects x and y, there always exists some mental object z, which stands in the hierarchical system above x and y. However, in this case, x and y can be incomparable with each other [7].

We get a (in principle, infinite) tower of mental spaces. This is a new type of cerebral mental hierarchy, i.e., the hierarchy of mental spaces. Recall that each of these spaces is a hierarchical tree. In particular, if the original tree is identified with tree *I*-states generated by the brain, we obtain an infinite hierarchical tower (hierarchical) mental space, which "relies on" the brain. Of course, we currently do not have experimental data (from neurophysiology and cognitive sciences) that could be interpreted as evidence of the existence of a vertical hierarchy of mental spaces. Some indirect evidence of the existence of towers of mental space, or rather, the brain's ability to operate simultaneously in several mental spaces, i.e., to process cognitive information of different mental levels in parallel.

Note that the parallelism introduction in this model of a hierarchical tower of mental spaces does not mean independence. The *I*-states of the lowest level form associations, which are the *I*-states of the next level. Thus, the most primitive *I*-states enter through the hierarchy of mental spaces into *I*-states of the highest mental level. It is possible that functioning in a tower of mental spaces is the basis of the brain's truly limitless informational capabilities.

This model does not exclude that, for example, the human brain can function in an endless tower of mental spaces. This will mean that the final physical system – the brain – can have endless information power. But even if the brain can use only a finite number of K floors of the hierarchical tower of mental spaces, then its information power is significantly greater than the power of a cognitive system using only the first floor, for example, only *I*-states produced by a neural network. Calculations show that information power grows linearly with increasing K. The value of K can be used as a numerical characteristic of the level of mental development. It is quite natural to assume that K grew in the course of evolution, reaching the highest of the %value in animals and humans. Moreover, K may depend on the species or even the individual. Although, in principle, the emergence of the human mind could correspond to the jump from finite K to infinite [7].

Leaving aside the hypothetical possibility of creating hierarchical mental towers, starting from some fixed ultrametric mental space X, let us return to a model that uses only X. It is natural to assume that different cognitive systems generate various spaces X. In particular, mental spaces can be generated in the form of different p-adic trees. There are 2-adic, 3-adic, and ... cognitive systems. However, it does not follow from the above that, for example, each person has their p (2-adic person, 3-adic person, ...). Different subsystems of the same brain can generate different p-adic trees. For example, there can be mental spaces arising in the form of $X = Q_5 \times Q_7 \times Q_{11}$, as well as more general ultrametric spaces.

After the Russian Television broadcast "At Gordon's," where the professor of mathematics expounded p-adic models of thinking in a conversation with one of the founders of p-adic physics, also a professor of mathematics, a security guard at Steklov Institute of Mathematics asked his interlocutor: "Tell me, professor, but are my brains 2-adic or, for example, 7-adic?"

One can use the general theory of metric spaces to describe mental processes. In particular, the possibility of representing physical metric spaces using mental ultrametric spaces is under study. The inverse problem of embedding an ultrametric mental space into a physical Euclidean space is also considered. An amazing topological fact (theorem of A. Lemin) is the impossibility of embedding an ultrametric space containing $n + 1$ points into R^k, $k <$ n. In particular, only a mental space containing four points can be embedded into the Euclidean space R^3. Even a five-point mental space cannot be nested in R^3.

Thus, the physical representation of a mental space containing hundreds of thousands of mental points requires a Euclidean space of unthinkable dimensions. In particular, the physical Euclidean image of the human mental space – the brain – arises from projecting a huge number of mental points onto each point of the physical area of the brain. Note that an infinite p-adic tree can be isometrically embedded only in an infinite-dimensional Hilbert space.

In what direction to proceed further on the path to creating an artificial intelligence system? It is crucial to simulate the higher mental activity: model selection, training, manic and depressive states, homeostatic states, habituation, imprinting, i.e., instant subcortical learning.

The most important feature of the Freudian description of the mental world is the reality of this world. For Freud, ideas, desires, feelings, experiences are no less real than, for example, mountains, houses, horses, ... For Freud, mental processes are no less real than physical and chemical processes. Ideas, desires, feelings, emotions, and experiences interact in the same way as physical bodies do. For Freud, mental forces are no less real than physical forces: "I have therefore confirmed that forgotten memories have not disappeared. The patient is still possessed by these memories and they are willing to enter into an association with what he knows, but some force prevented them from being conscious and forced them to remain unconscious. The existence of such a force could be accepted quite confidently since the corresponding strain was felt when trying, in contrast to it, to bring unconscious memories into the patient's consciousness. One felt the strength that supported the painful state, namely, the patient's resistance" [8].

By introducing the corresponding field of forces, we get the corresponding mental field. Thus, it is quite natural to try to encode all mental objects that arise in Freud's psychoanalytic scenarios with the help of some mathematical structures and try to model the mental processes, in particular, the emergence of complexes within the framework of mathematical models. Undoubtedly, this is a highly complex problem and the p-adic model can describe only some features of mental behavior.

The most important postulate of Freudianism is the one of the determinism of mental processes. Roughly speaking, the mental trajectory is determined by the initial conditions (for example, childhood experiences) and the corresponding field of mental forces.

The mental field can be treated as an information field. The natural question about its measuring arises. Another question is about coupling with physical fields, e.g., the electromagnetic field generated in the brain. An important step in this direction was recently done in [9]. Here, EEG signals from the brain were transformed with the aid of a clustering algorithm into dendrograms, which, in turn, can be algebraically represented by p-adic numbers. A corresponding "mental field" was reconstructed as Bohm potential on the p-adic configuration space. This approach was used for medical diagnostics of epilepsy.

No diagnostic or predictive instruments to help with early diagnosis and timely therapeutic intervention are available as yet for most neuropsychiatric disorders. A quantum potential mean and variability score (QPMVS) was developed to identify neuropsychiatric and neurocognitive disorders with high accuracy, based on routine EEG recordings. Information processing in the brain is assumed to involve the integration of neuronal activity in various areas of the brain. Thus, the presumed quantum-like structure allows quantification of connectivity as a function of space and time (locality) as well as instantaneous quantum-like effects in information space (non-locality) [9].

V. Making the final decision in the brain. How to create effective artificial intelligence

In [10], Michio Kaku compares the brain to a large corporation. This idea has a right to exist; it can explain some interesting properties of the brain:

- The bulk of the information is in the "subconscious," i.e., the general director, fortunately, has no idea about the deep streams of information continuously circulating through bureaucratic channels. Moreover, only a tiny fraction of the information ultimately ends up on the desk of a senior executive, who can be compared to the prefrontal cortex. The general director only gets to know the data that is important enough to merit his attention; otherwise, his activity would be paralyzed by the avalanche of unnecessary information.
- Probably, such an organization of brainwork is a by-product of evolution since, under critical conditions, our ancestors could not afford to overload the brain with superficial subconscious information. Fortunately, we do not notice all the trillions of operations that our brain constantly performs. Having met a tiger in the forest, one does not have to think about the state of their stomach, toes, hair, and others at that moment but just needs to remember how to run faster.
- "Emotions" are quick decisions that are self-born at a low level. Since rational thoughts take a long time, and, in a critical situation, there is no time to think, low-level areas of the brain must quickly assess the situation and make a decision (generate emotion) without permission from above.

Thus, emotions (fear, anger, horror, etc.) are instantly appearing alarm flags, the command to which is given at a low level and the purpose of which is to warn the control center about a potentially dangerous or difficult situation. Consciousness has virtually no control over emotions. For example, no matter how we prepare for a public speech, the nervous tension will not disappear [10].

Rita Carter, the author of "Mapping the Mind" paper, writes: "Emotions are not feelings at all, but a set of physiological survival mechanisms that emerged as a result of evolution. Their task is to direct us away from danger, towards what may be useful" [11].

There is a constant struggle for the attention of the leader, but there is no single homunculus, central control panel, or Pentium processor making decisions; instead, various local centers within the leadership are in constant competition with each other for the director's attention. Therefore, thoughts do not go in a smooth continuous sequence, all kinds of feedbacks compete with each other, thereby creating a real cacophony. The concept of "I" as a single integral entity, continuously making all decisions, is just an illusion generated by the subconscious.

We ourselves feel that our consciousness is one, that it continuously and evenly processes information and fully controls all our decisions. However, brain scans give a completely different and objective picture.

Professor at the Massachusetts Institute of Technology (MTI) Marvin Minsky, one of the founding fathers of the Laboratory for Artificial Intelligence, said that the human mind is more like a "society of minds," consisting of sub-modules that are constantly fighting among themselves.

Harvard psychologist Steven Pinker explains how consciousness arises from all this confusion: ***consciousness is like a storm raging in my head***. "John intuitively feeling that there is a guideline of "I" that sits in our brain's control center, looks at the screen with the data from the senses, and pushes buttons to send commands to our muscles is just an illusion. Rather, consciousness is a vortex of events distributed throughout the brain. These events compete for attention, and when one of them manages to out-shout all the others, the brain rationally substantiates the result retroactively and fabricates the impression that everything happened under the control of a single center."

Final decisions are made by the general director in the control center. Almost all the bureaucracy exists to collect and organize information for the general director, who only meets with the department heads. He tries to bring to a common denominator all the conflicting information coming to the command center. All intrigue ends here. The general director in the prefrontal cortex has to make the final decision. Whereas in animals most decisions are made instinctively, humans make high-level decisions after carefully analyzing and sifting through the information coming from the senses [10].

Information flows are hierarchical. Since a huge amount of information must pass both up to the management office and down to the performers, this information must be

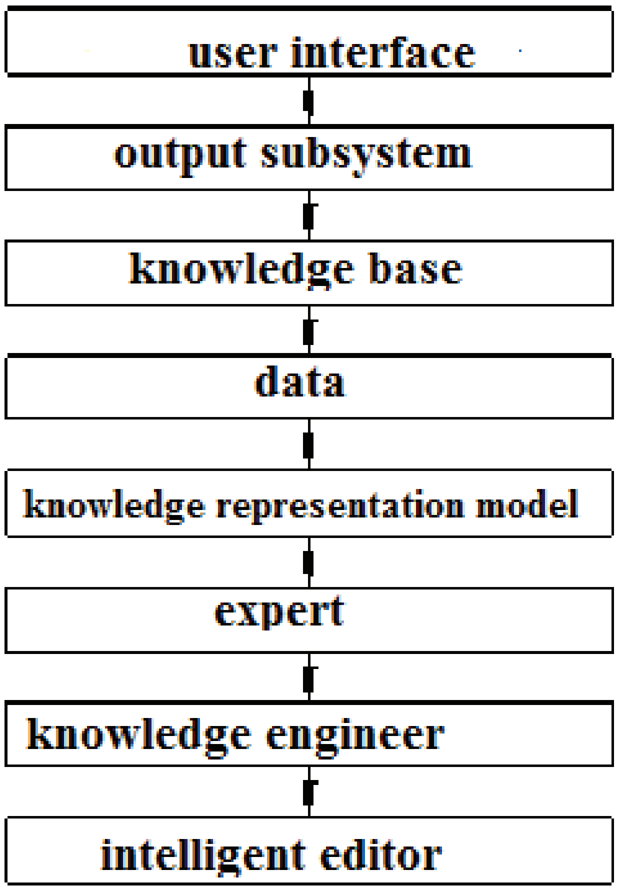

Fig. 3. Structure of the expert system.

organized into complex systems of embedded networks with many branches. Imagine a spruce tree with a guiding center at the top and a pyramid of branches below, leading to many less significant centers.

There is, of course, a difference between the bureaucratic system and the structure of thinking. It is known that the first rule of any bureaucracy is that "it expands and fills all the allocated space". Wasting energy, however, is a luxury that the brain cannot afford. The brain only consumes about 20 watts of power (like a weak incandescent lamp), but this is probably the most it can take without depriving the rest of the body of functionality. If the body generates more heat, the tissues will fail. Therefore, the brain constantly conserves energy and uses all sorts of tricks for this. These clever ways are invented by evolution to simplify various actions.

VI. Artificial intelligence systems

Consider two historically established directions of building artificial intelligence systems [1–3]:

- expert systems,
- neural networks.

The historical aspects of the development of these directions will not be presented here (this was done approximately in the same period but by completely different groups of specialists). The distinction between directions is somewhat confused by the partial commonality of terminology (such as "artificial intelligence," "decision making," and others). Genuine differences are revealed

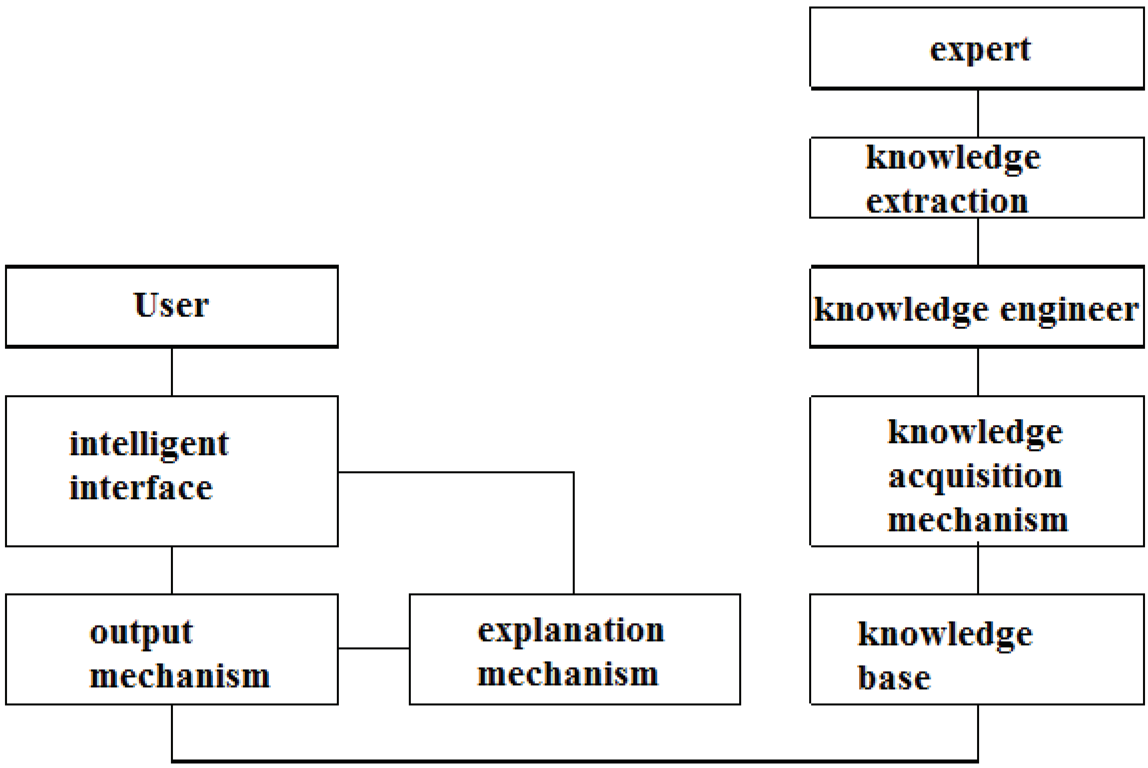

Fig. 4. The architecture of the expert system.

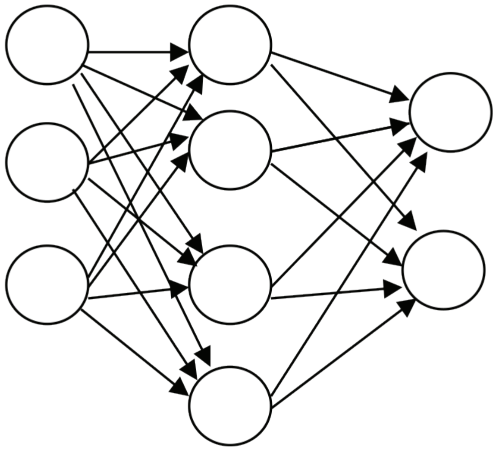

Fig. 5. An example of a simple neural network.

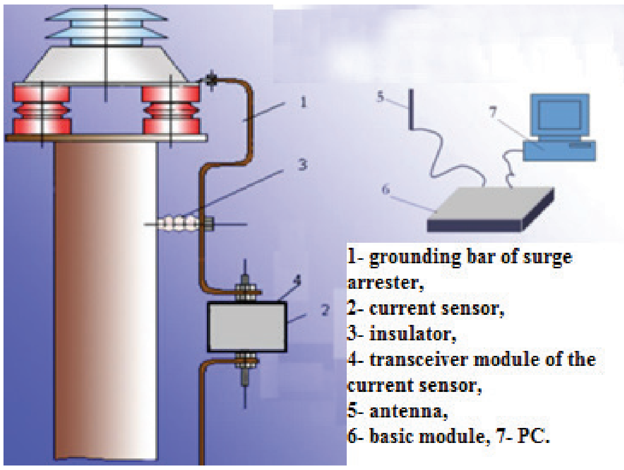

Fig. 6. Structural diagram of a remote control device for leakage current of the surge arrester.

if we pay attention to the semantics of the main class of concepts in the corresponding intelligent models (Fig. 3).

In expert systems [12–14], these are models of reasoning for specialist people. Reasoning models are often based on production rules (expressions like "if… then"). Access to the rules on the limited natural language allows accompanying the decision-making in expert systems with explanations that are clear to users. This method is used to create some intelligent expert systems, including energy applications. An example of the architecture of the expert system is shown in Fig. 4.

In *neural networks*, the basic semantic elements are models' neurons and neuron layers (input, output, intermediate) (Fig. 5) [12]. Large amounts of data are associated with neuron models (the so-called "big data"). A partially trained neural network can be used for other tasks as well. The successful application of neural networks is known in strategic games, recognition of images, etc. A significant drawback of the neural network application is a complete absence of explanation of the system's actions. Knowing how apply layers of neurons to new tasks is a skill close to the invention. A typical example is various variants of human face recognition [12–14].

Speaking about the speed of intelligent systems, one should note the fundamental advantage of expert systems – they can use "operational results" to start a solving process, while in neural networks, one has to start from afar (from the neuron model).

Currently, most experts believe (based on the achievements of neural networks in games and in the military field) that neural networks have finally won the competition in intellectual areas. A more cautious conclusion, however, seems attractive: for "routine" operational tasks (such as automated control systems for electric power grids), neural networks should be considered priority expert systems (tasks of analyzing graphic images should be attempted by other methods). There is no alternative to neural networks when working with "big data" [5–14].

Let us consider several examples of using neural networks in the electric power industry to monitor the state of electrical equipment.

VII. Remote control device for leakage current of surge arrester

The current flowing through the surge arrester (leakage current) is a geometric sum of capacitive and active components, with the predominant component of the capacitive current during normal operating conditions (Fig. 6).

This device has several advantages, unlike standard diagnostic methods for surge arresters (conduction current measurement):

1. Wireless communication of measuring sensors and measuring module (up to 1000 meters).
2. Efficiency in the processing and transmission of data received in measuring sensors to the user.
3. Short response time to changes in measured values and quick notification of the user in case of abnormal changes in measured data.
4. Sensors form a system for receiving and transmitting data with the help of transmitting and receiving modules.
5. Stability of the system. Failure of a sensor (several sensors) does not lead to a malfunction of the system.
6. The number of measuring sensors working with one measuring module (personal computer) can be 100 or more.
7. The total length of the system can be tens of kilometers.
8. Ability to connect to an Ethernet network via TCP/IP protocol to obtain remote access to the system at the request of the customer.
9. The GPS module, a global positioning system, when used in the sensors, provides information about the exact geographic location of the sensors and real time, which allows them to synchronize their work [15].

The current passing through the surge arrester flows through the grounding conductor, in the cut of which the

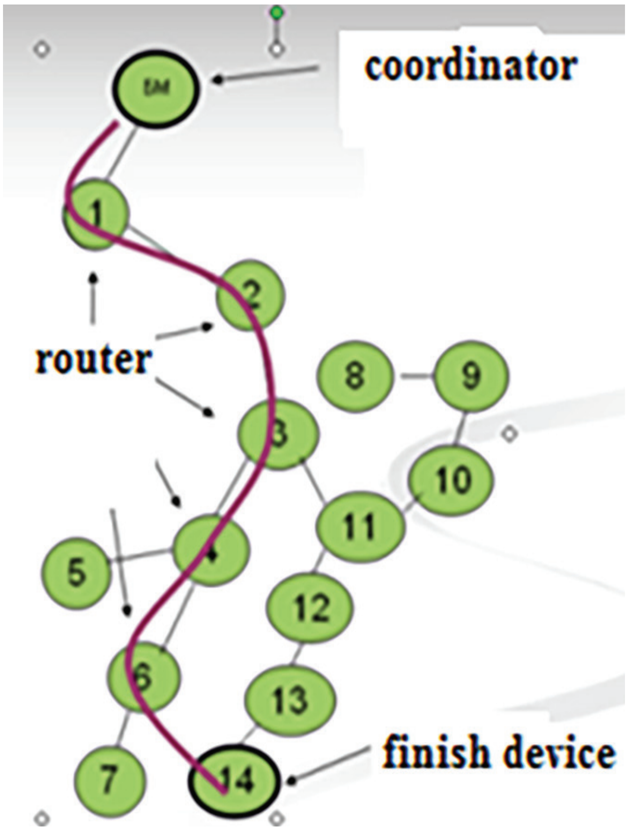

Fig. 7. An example of organizing the communication route of the current sensor No. 14 with the basic module.

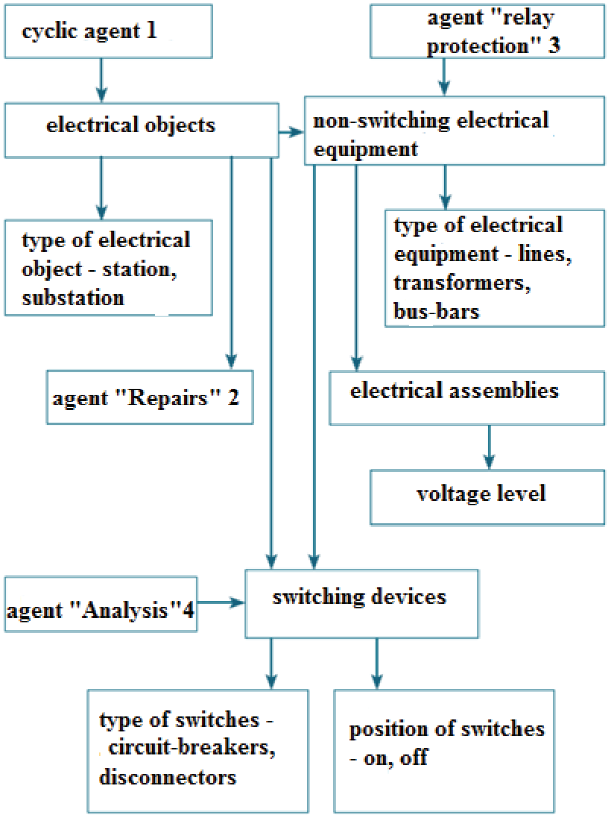

Fig. 8. Topological model of the primary network for dispatch control tasks.

measuring module (MM) is installed. Current is measured using a resistive shunt located inside the MM. Data from the MM is transmitted using a transceiver device based on ZigBee technology. The MM conducts primary current measurement, temperature measurement and determines the triggering of surge arrester when the current exceeds a certain value. The basic module (BM) communicates with the measuring modules and configures the MM network. The basic module provides receiving and transmitting functions to transfer information from the MM to a personal computer and data processing in software installed on a PC. The software performs digital signal processing. Maximum effective values of currents (capacitive and active components) are determined.

The time interval of data collection is determined once a month, as well as in case of an abnormal increase in current. The report indicates the number of the current sensor, time, temperature, data array of the values of the flowing current. When the current exceeds a certain value, the time interval is reduced to 2.5 hours. In turn, the operator can request sensor readings at any time.

The wireless data transmission system based on the ZigBee technology allows organizing a radio network by connecting all devices in a single multilocular network. The advantage of the ZigBee technology is its stability. It is capable of organizing a radio network in the event of failure of one or several sensors in a single multimesh network, and signaling the failure of sensors (Fig. 7) [15].

The authors of [16] present the experience in the development and implementation of decision support systems based on machine learning algorithms in various tasks of the electric power industry, analyze the main errors and the consequences of their influence on the results of the operation of such systems in the electric power industry.

This is done on the example of the problem of predicting the photovoltaic generation introduced into the technological activities of electric power network [16].

VIII. “Smart” electrical grids for dispatching decisions

For “smart” electrical grids, we considered software tools based on artificial intelligence methods that perform new functions and increase the level of computer support for dispatching decisions [13].

One of the smart grid goals, in this case, is to ensure recovery after a breakdown. Therefore, particular attention is focused on the problems of diagnostics of emergencies, intelligent monitoring of the states of electrical networks, and planning of post-emergency restoration of power supply. A new type of software simulator (a simulator for analyzing emergencies) for dispatchers of electrical networks is considered in [13]

A multi-agent structure of an intelligent automated dispatch control structure was employed as part of artificial intelligence used.

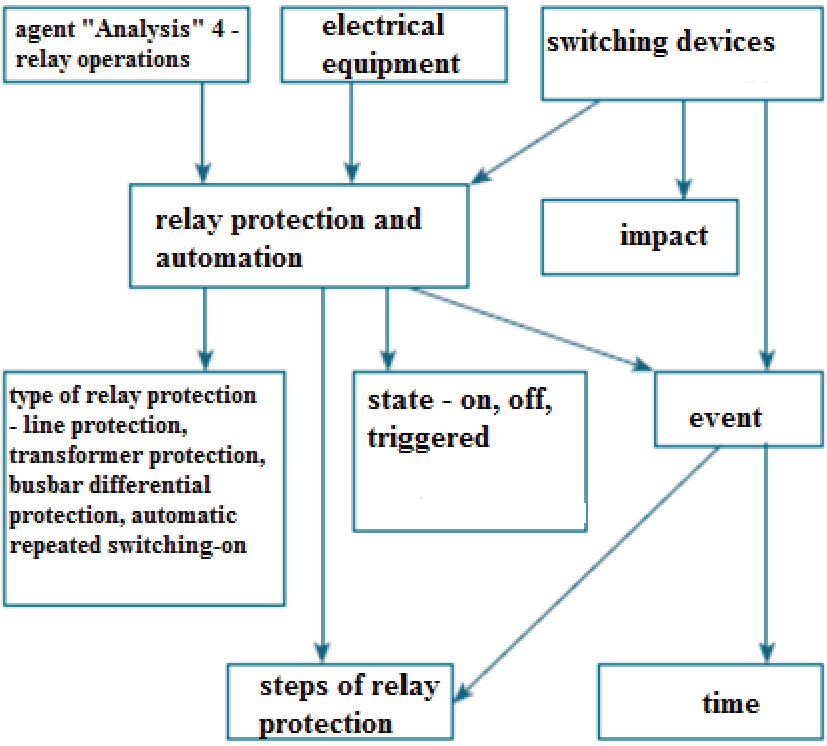

Fig. 9. Logical model of relay protection for dispatch analysis tasks.

The problem of analyzing technological breakdowns and accidents and the possibility of forming (based on the data of the operational information complex) an operational reference about an accident in the electric power system to facilitate and accelerate the investigation of technological breakdowns and accidents at substations (with examples of investigation acts) are also considered.

The concept of "volumetric" decision-making is introduced, reflecting the participation in decision-making of groups of specialists with different competencies. In this case, the concept of an expert system with a "bulletin board" is used.

The possibility of using the concept of extreme programming is considered to facilitate the transformation of the operational experience of technologists into the formalisms of a natural language expert system.

For definiteness, this paper assumes the use of the MIMIR expert system (shell) since this system has several successful applications in electric power problems [12].

"Intelligent" dispatching systems (IDS) [12, 13] are usually called systems that contain, in addition to traditional functions (collection of operational information, maintaining real-time databases and archives, performing calculations, graphical presentation of information in the form of mnemonic diagrams, graphs, diagrams, generation reports) and intelligent functions (based on knowledge [13]), such as:

- situational analysis of the control object, including the analysis of events and situations,
- determination of the necessary actions of the operator in the event of emergencies,
- blocking against unauthorized actions of the operator,
- maintaining knowledge bases of real time [17–20].

Traditional dispatch systems do not provide operating personnel with a sufficient level of information support for the operational dispatch control of electric power grids in emergencies. Receiving images of circuits with the positions of switching devices and values of electrical parameters indicated on them, the dispatcher must "think themselves" whether the situation is abnormal, what is the cause of the situation, what actions need to be taken to restore the normal situation. The cost of human error in making such decisions can be very high.

The dispatching systems existing for electric power grids (at least domestic ones) have no intelligent functions. At present, the prerequisites for changing this situation have emerged, there are real-time domestic expert systems tested in operation [17, 18]. Ensuring that information about relay protection and control systems is entered into the IDS is no longer a serious problem (see, for example, Siemens ACS – proavtomatika.ru).

The implementation of the IDS functions is achieved by including some intelligent agents (IA) in the system built programmatically based on the technology of expert systems, and algorithmically – on a set of technological instructions.

Such a system with elements of artificial intelligence should recognize precisely abnormal situations, separating them from standard ones, such as, for example, shutting down equipment elements to be taken out for repair on request.

When analyzing an abnormal situation (technological breakdowns and accidents at substations), the system must determine:

- source of technological disturbances (for example, short-circuit on one of the equipment elements);
- work of automatically repeated switching-on (successful or unsuccessful);
- failures in the operation of circuit-breakers;
- tightening of the switch of circuit-breakers;
- failures in the operation of relay protection and automatic controls;
- excessive or non-selective operation of relay protection and automatic control devices;
- disconnection of equipment elements (transmission lines, transformers, bus-bars).

This data is minimally necessary for dispatching and operating personnel to assess the situation in the electrical network and begin planning measures to prevent the development and eliminate technological disruptions.

Some scientific papers [17–26] consider the intelligent functions of automated dispatch control systems (ADCS). The effectiveness of these functions was shown when describing the situations and generating advice for dispatching personnel in emergencies. These functions use the platform of expert systems, and the formalism of forming the reasoning models of technologists is applied [16]. The real-time operation of the ADCS complex requires that the architecture of the software of this complex be considered. At the same time, relying on a variety of functionally different workstations, it is advisable to distribute intelligent functions so that they correspond to the experience of various technologists and, at the same time, only the part of the overall task "adjacent" to the experience of the relevant specialists (in particular, the analysis of the situation) is performed. This approach is consistent with the concept of multi-agent systems of artificial intelligence [12, 20–26].

Intelligent programs for analyzing the situation for ADCS are functionally different and use different sections of the system's knowledge. It is appropriate to organize the execution of these programs by different intelligent agents, i.e., relatively simple modules, each of which uses its own section of knowledge and has its own conditions of initiation. Since ADCS is normally implemented as a computer network, intelligent agents are localized in computerized workstations for various specialists.

Figure 8 shows an example of a semantic network structure for dispatching tasks in electric power grids. Concepts of "semantic network to represent relay protection" are combined into homogeneous semantic groups. Interaction between users and an intelligent system can be organized with the help of a limited natural language.

This interaction is based on natural language issues.

A semantic network for representing relay protection and automatic controls is shown in Fig. 9.

The structure of such an automated dispatch control system contains at least four intelligent agents.

IA1 is a cyclically functioning agent. Based on the results of operational information processing (switch positions), it forms the current switching model of the network and records the events of equipment shutdown and separation of network sections. It uses information about the actuation of relay protection and automatic devices.

IA2 (agent "repair") is initiated at events disconnecting equipment (which are fixed by IA1 and processed in IA4), given (emergency) shutdown requests for the respective items of equipment, and adjustment, where necessary, the appropriate limitations of operating conditions [12, 16–26].

Formalized operating instructions stored in the Knowledge Base of the system are used for automatic operational processing of repair requests. The instructions specify restrictions on the operating parameters (these are normally active power flows in the control cutsets), which must be observed when disconnecting the equipment named in the application. These restrictions can be of two types: those imposed on the duration of the claim and the restrictions on the switching times of switching devices. Inconsistency between the restrictions on the application being processed and the restrictions on the already resolved applications may lead to the refusal of one of the conflicting applications or to the most severe restriction on the time of "imposition" of applications. When repairs are terminated on an already resolved request due to a failure, the emergency readiness time required to change the repair schemes of the corresponding facilities is taken into account. Module IA2 compiles a table of repairs for dispatchers with appropriate restrictions [19–23].

IA3 (agent "Relay protection and automatic control equipment") operates cyclically and detects events actuating relay protection devices and automatic controls of an object.

The IA3 functions, apart from other specifical "relay" tasks, include the formation of events associated with the operation of relay protection and automatic equipment and emergency control devices. The source of this information is the object data concentrators. Since this paper considers

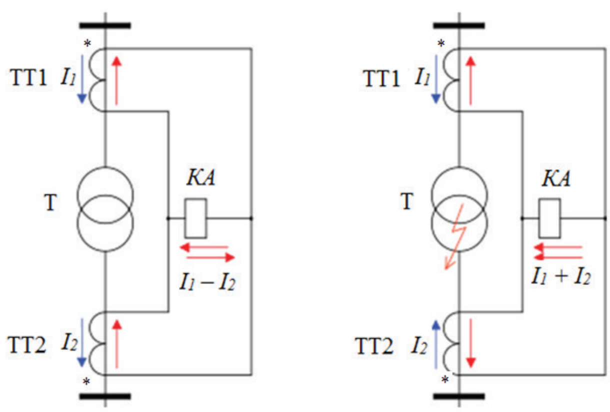

Fig. 10. Differential relay, a) no internal damage, b) internal damage.

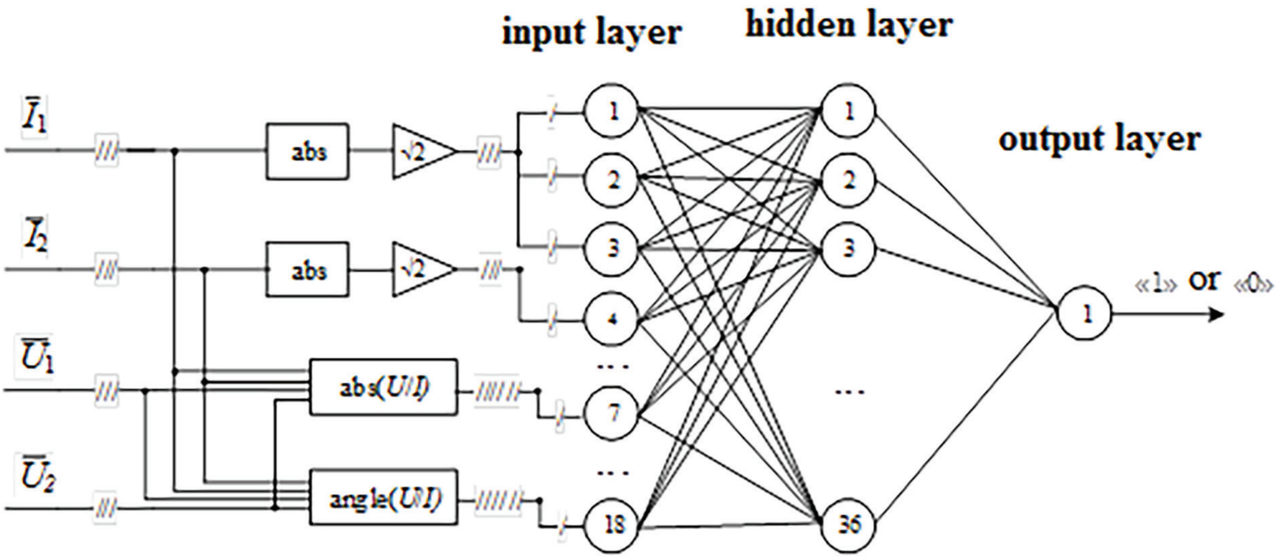

Fig. 11. The structure of the power transformer protection algorithm based on a neural network.

only dispatching express analysis of situations, the events triggering the relay protection and automatic devices (in which the "correct" sequence of events is significant rather than accurately recorded time of the event) have the same status as the events triggering switching devices (recorded in IA1). In the future, the automation of a complete "relay" analysis can make the IA3 functions complicated.

IA4 (agent "Analysis") is initiated when detecting relay operation, equipment shutdowns, separation of network sections. This agent generates a description of the situation and (if necessary) displays advice texts for the dispatcher [23–26].

Diagnostics of electrical equipment faults and overhead power line condition by monitoring systems (Smart Grid) is investigated in [27], while [28–32] focus on ensuring reliable operation of electric networks and experience in testing of digital substation primary equipment and relay protection.

IX. Application of neural network algorithms for the recognition of turn-to-turn faults in power transformers

The application of neural network algorithms to recognize turn-to-turn faults in power transformers is studied in [33]. One of the most difficult problems in protecting power transformers is to detect small-scale internal faults.

The differential protection scheme is based on the principle that the input power of the power transformer, under normal conditions, is equal to the output power. Under normal conditions, no current flows into the current coil of the differential relay. When a fault occurs within the protected area, the current balance is disturbed, the relay contacts close and a signal is sent to certain circuit-breakers to trip the faulty equipment. Differential relay KA compares primary and secondary currents of a power transformer. Current transformers (TT) are used to reduce the magnitude of primary currents so that their secondary currents are equal.

Figure 10 shows a differential relay in its simplest form. The polarity of the current transformers is chosen such that the current circulates without passing through the relay under normal load conditions and external faults.

Thus, based on the above studies, the most effective structure of the neural network is selected. The structure of the selected configuration is shown in Fig. 11.

The assessment of the operation of differential protection relies on an already created algorithm for the operation of differential protection and a model of power transformer with a turn-to-turn fault [33].

The principles of constructing intelligent relay protection of electrical networks, as well as an algorithm for identifying the damaged section on cable-overhead power lines based on the recognition of wave portraits, are investigated in [34–36].

X. Conclusion

1. Two historically established directions (expert systems and neural networks) of building artificial intelligence systems are studied in detail.
2. The parallels and analogies with the work of the human brain are considered to use the algorithms and principles of the brain to create artificial intelligence.
3. The studies on the creation of a human brain model to be used in the construction of an artificial intelligence system are considered.
4. It is noted that the high performance of information processing in the human brain can only be explained by the parallel operation of many relatively slow neurons and a large number of mutual connections between them.
5. The processes taking place in the human brain cannot be embedded in the coordinate system of the Euclidean

space R^3, so one can try to embed them in other types of spaces, for example, multidimensional.

6. It is emphasized that the theoretical foundations of neural networks were laid in the 1940s.
7. The hierarchical structure of the brain is confirmed by the existence of towers of mental spaces, the ability of the brain to simultaneously operate in several mental spaces, i.e., to process in parallel cognitive information of different mental levels.
8. The physical representation of a mental space of hundreds of thousands of mental points requires a Euclidean space of inconceivable dimension. The brain is a result of the projection of a huge number of mental points onto each point of the physical region of the brain. Therefore, an infinite *p*-adic tree can be isometrically embedded only in an infinite-dimensional Hilbert space.
9. Consciousness represents vortices of events distributed throughout the brain that competes for the brain's attention. Thus, the result appears to us when one of these vortices of consciousness manages to become dominant over all the others, and the brain rationally justifies the result retroactively, and it seems to us that all consciousness is under the control of a single center.
10. Thus, based on the "developments" of the human brain, created over millions of years of evolution, the creation of an artificial intelligence system (we do not have these millions of years) should be guided by several principles:
    - the parallel operation of many relatively slow processor chains and a large number of mutual connections between them,
    - the hierarchical structure of information flows will make it possible to simultaneously operate in several spaces, i.e., to process information of different levels concurrently,
    - the work of such a complex structure as artificial intelligence is possible only as an endless tree, at the top of which there is a guiding center, and below – a pyramid of branches leading to a multitude of less important centers, and which can be isometrically embedded only in an infinite-dimensional space.
11. Attempts can be made to teach (train) neural networks and use them in pattern recognition tasks, strategic games, and others.
12. Expert systems are of priority for "routine" operational tasks in the electric power industry (such as the automated control system for power grids).
13. The system of wireless transmission of data on the leakage current through a surge arrester based on ZigBee technology allows organizing a radio network by uniting all devices into a single multi-mesh network, which is analogous to a neural network.
14. High-quality information support of dispatching decisions in emergencies requires the systems for the dispatching control of electrical networks to be implemented based on intelligent agents relying on expert systems technology.
15. It is necessary to ensure that the dispatching system is provided with a sufficiently complete volume of tele-signaling of data on the position of switches and data on composition and operation of the relay protection and automatic devices.
16. A sample of an intelligent dispatching system for managing electrical networks has been developed.
17. Analysis of emergencies in a networked intelligent system is the basis for building an intelligent system (a dispatcher's advisor for electrical network companies) and should be performed at two levels: the substation and the electrical network.
18. When building complexes of automated dispatching control systems for electric power systems and power grids, it is advisable to use a multi-agent structure of intelligent functions, with the intelligent agents localized at the workplaces of technologists.
19. "Volumetric" intelligent ADCS in electrical grids should use the architecture of intelligent systems with a "Notice Board" and obtain a computer certificate of a technological breakdown, which will substantially facilitate the subsequent analysis of the accident with the participation of human specialists.
20. The concept of combining intelligent natural language systems with the extreme programming methodology opens up the possibility of relatively simple and effective development of intelligent agents while minimizing the participation of professional programmers in this development.
21. The recognition of internal turn-to-turn faults in the transformer winding has been investigated, and an algorithm for the power transformer protection based on a neural network has been created.

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Investigations on OTC-MPPT Strategy and FRT Capability for PMSG Wind System with the Support of Optimized Wind Side Controller Based on GWO Technique

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Abstract **— Stable operation of permanent-magnet synchronous generator-based wind turbines (PMSG-WTs) is a challenging and complicated objective. Dealing with the hard situations and complex operations of the PMSG-WTs has recently become a hot issue in modern power systems. The abilities of PMSG-WT to ride over faults and operate at maximum power point (MPP) are the most critical requirements for national grid regulations. To maintain the system's reliability, PMSG-WT should remain linked to the grid during normal and abnormal conditions. Furthermore, PMSG-WT has the potential to inject reactive power during failures. It produces active and reactive power to maintain grid voltage immediately after the fault is cleared. This research uses MATLAB/Simulink to investigate the operation at MPP during wind speed changes and FRT capability during three-phase fault of PMSG-WT to validate the support of grey wolf optimizer (GWO)-based PI controllers at the wind side converter. The findings reveal that, when PMSG-WT is exposed to a fault, active and reactive power react in a complementary manner, i.e., active power to the grid drops, and injected reactive power rises to stabilize the system. While during wind speed changes the system achieves MPP operation using an optimal torque control strategy, and the output power follows the wind variations.**

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Index Terms: **Grid code compliance, grey wolf optimizer (GWO), grid fault, MPP, PMSG-WT.**

List of abbreviations

ANNs – artificial neural networks
APA – affine projection algorithm
CSA – cuckoo search algorithm
FACTS – flexible alternating current transmission system
FLC – fuzzy logic controller
FRT – fault ride-through
GSA – gravitational search algorithm
GSC – grid-side converter
GWO – grey wolf optimizer
GCC – grid code compliance
OTC – optimal torque control
PI – proportional-integral
MSC – machine-side converter
MPPT – maximum power point tracking
PSO – particle swarm optimizer
PMSG – permanent magnet synchronous generator
WOA – whale optimizer algorithm
WT – wind turbine
WECS – wind energy conversion system
BCS – braking chopper system
BA – bee algorithm
ESA – energy storage apparatuses
WSC – wind side converter

I. Introduction

In today's electricity system, renewable energies play a critical role, with wind energy having the quickest implementation in many nations [1, 2]. Wind energy is less expensive than other renewable energy sources, delivers electricity with less environmental impact, and is more reliable [3]. The global capacity of installed wind power from 2001 to 2022 is presented in [4]. Several nations have created operational guidelines for the integration of

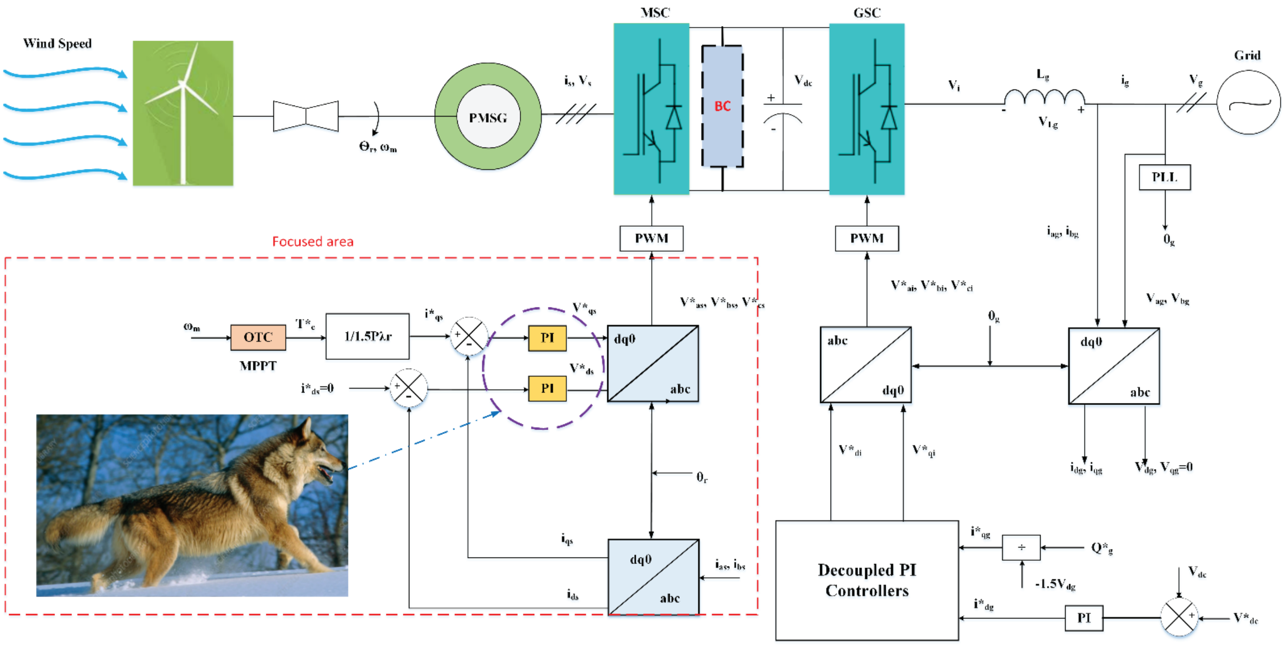


Fig. 1. The addressed system.

dispersed power based on grid codes. Due to their unique characteristics, such as variable speed and real-time power management, permanent-magnet synchronous generators (PMSGs) are the most extensively utilized wind energy conversion devices [5, 6].

During typical operating conditions, both the grid side and wind side power converters are used to manage DC link voltage, actual power transfer, and reactive power transfer. PMSG-based wind systems are often isolated from the grid during faults to prevent the damage of the fully rated back-to-back power converter and DC link capacitor [7, 8]. Grid code, however, mandates that a certain number of PMSGs be linked to the grid during fault events and thereby assist the grid. For PMSGs to support the PMSG-connected grid system by regulating real and reactive power and protecting the power electronic components in the system, appropriate fault ride-through (FRT) methods are required. Moreover, the application of optimization techniques or artificial intelligence-based controllers in wind side converters helps improve PMSG's performance [9, 10].

Robust and adaptive control systems must be used to deal with the nonlinearity of wind systems. Over the last two decades, meta-heuristic optimization techniques have become very popular. Length of the training procedure and convergence time are the shortcomings of artificial neural networks (ANNs) [11]. Although fuzzy logic control (FLC) is easy to build, cost-effective, and has better performance with the system's nonlinearities, it requires deep knowledge in design operation [12, 13]. There are several statistical and conventional techniques like the Taguchi technique, response surface method (RSM) [14], artificial neural network (ANN), and affine projection algorithm (APA) [15]. They are applied in fine-tuning proportional-integral

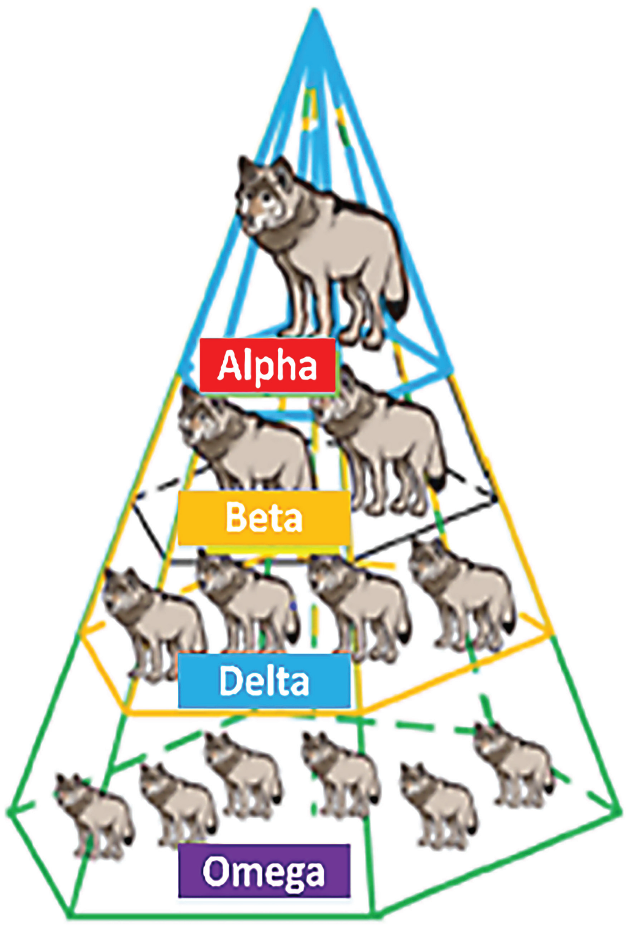


Fig. 2. Hierarchy of grey wolf (dominance decreases from the top down).

Fig. 3. Hunting actions of GWs [23].

(PI) controllers employed in the regulatory system of different power system components. These techniques, however, depend on the initial values. Thus, meta-heuristic algorithms such as particle swarm optimizer (PSO) [16], cuckoo search algorithm (CSA), whale optimizer algorithm (WOA) [17], bee algorithm (BA) [18], gravitational search algorithm (GSO), and differential evolution algorithm are competitive solutions for fine-tuning the parameters of PI controllers [15].

As the penetration of wind energy increases, the need to address FRT capability issues becomes more critical. Earlier, WTs were allowed to trip when a voltage dip occurred. During this voltage dip, active power provided to the grid by the WECS is instantaneously reduced. This power becomes at least temporarily lower than the mechanical power available at the rotor, hence, the rotor speed of the wind generator increases [19]. Controllable FRT capabilities used for PMSG wind systems, including pitch control system, modified converter system, and FLC-based GSC operation are discussed in [20]. In addition, there are many hardware solutions, like braking chopper system (BCS), FACTS, and energy storage devices (ESD) [7, 21].

This work investigates an OTC-MPPT strategy during wind speed change and FRT capability of PMSG wind system using BCS at the DC-bus in the course of faults with the support of optimized wind side controller based on GWO technique. The GWO efficacy is tested in a variety of situations. The paper structure is as follows: Section 2 focuses on the description of the system under consideration. A mathematical model of the GWO and its MSC application are considered in Sections 3 and 4, respectively. Simulation results are introduced and discussed in Section 5. Section 6 presents the conclusion.

II. Description of the studied system

Figure 1 depicts the overall structure of the system under investigation. It consists of a WT model; PMSG, MSC, and GSC with their control; and a grid model.

A. A WT model

The WT model can be defined as follows [7, 17]:

$$C_P\left(\lambda,\beta\right)=0.5176\left(\frac{116}{\lambda_i}-0.4\beta-5\right)\exp^{-\frac{21}{\lambda_i}}+0.0068\lambda\ ,$$

$$\lambda=\frac{\omega_r R}{V_W},$$

$$T_m=\frac{P_m}{\omega_r},$$

$$T_m=J_{eq}\frac{d\omega_r}{dt}+B_{eq}\omega_r+T_e\ ,$$

where C_P, λ, ω_r, J_{eq}, B_{eq}, T_e, T_m are the studied WT parameters [17].

B. A PMSG model

The PMSG concept is fully defined in [17] and can be represented as follows:

$$V_{ds}=R_s I_d+\dot{\lambda}_d-\omega_e\psi_q\ ,$$

```
Initialize the grey wolf population Xi (i = 1, 2, ..., n)
Initialize a, A, and C
Calculate the fitness of each search agent
Xα=the best search agent
Xβ=the second best search agent
Xδ=the third best search agent
while (t < Max number of iterations)
    for each search agent
            Update the position of the current search agent by equation (3.7)
    end for
    Update a, A, and C
    Calculate the fitness of all search agents
    Update Xα, Xβ, and Xδ
    t=t+1
end while
return Xα
```

Fig. 4. Pseudo-code of the GWO algorithm [23].

$$V_{qs} = R_s I_q + \dot{\lambda}_q - \omega_e \psi_d \ .$$

The stator flux connection components can be written as:

$$\psi_d = L_d I_d + \psi_{pm},$$
$$\psi_q = L_q I_q.$$

The symbol T_e can be defined in the following way:

$$T_e = \frac{3}{2} n_p \left(\psi_d I_q - \psi_q I_d\right) = \frac{3}{2} n_p \left(\psi_{pm} I_q + I_d I_q \left(L_d - L_q\right)\right).$$

For the surface-mounted PMs sort, $L_q = L_d$. Then, T_e can be written as tracks:

$$T_e = \frac{3}{2} n_p \left(\psi_{pm} I_q\right).$$

III. A GWO approach

This study employs GWO to find the best controller settings. The four types of grey wolves (GWs) used to model the optimization technique's leadership structure are alpha (α), beta (β), delta (δ), and omega (ω) (Fig. 2). The hunters' choice is made by the leaders (α), as seen in Fig. 2. Wolves (β) assist in decision-making and also serve (α) as a wolf's counsel and the pack's enforcer. The (ω) wolves serve as scapegoats. This helps to keep the pack satisfied and the dominance structure in place. If a wolf is not a dominant α, β, or ω, it is described as subordinate [18]. The feeding behavior of GWs is seen in Fig. 3. In addition, the pseudo-code of the GWO algorithm is presented in Fig. 4.

The GWO mathematical formula seeks to mimic and recreate the numerous steps that GWs go through hunting prey, which are: social hierarchy (A), surrounding prey (B), hunting (C), attacking prey (D), and searching for prey (E).

The GWO concept is fully defined in [22] as follows:

$$\vec{D} = \left|\vec{c}\ \vec{x}_p(t) - \vec{x}(t)\right|,$$

$$\vec{x}(t+1) = \vec{x}_p(t) - \vec{A}\,\vec{D},$$

$$\vec{A} = 2\vec{a}\vec{r}_1 - \vec{a}\ ,$$

$$\vec{C} = 2\vec{r}_2\ \ ,$$

$$\vec{D}_\alpha = \left|\vec{C}_1\vec{x}_\alpha - \vec{x}\right|,\ \vec{D}_\beta = \left|\vec{C}_2\vec{x}_\beta - \vec{x}\right|,\ \vec{D}_\delta = \left|\vec{C}_3\vec{x}_\delta - \vec{x}\right|\ ,$$

$$\vec{X}_1 = \vec{x}_\alpha - \vec{A}_1\left(\vec{D}_\alpha\right),\ \vec{X}_2 = \vec{x}_\beta - \vec{A}_2\left(\vec{D}_\beta\right), \vec{X}_3 = \vec{x}_\delta - \vec{A}_3\left(\vec{D}_\delta\right),$$

$$\vec{x}(t+1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3}\ .$$

IV. MSC control with GWO

As seen in Fig. 1, the job of MSC is to manage the machine rotor speed for maximizing output power from the passing wind, based on GWO. Equation (1) shows the system optimization model with control cost. Table 1 indicates the selection of PI-GWO controller gains employed at MSC for MPPT utilizing the OTC method. The PMSG control cost optimization model is as follows:

$$\begin{aligned} Minimize\ F(x) = \int_0^T & W_1\left|I_d - I_d^*\right| + W_2\left|\omega_m - \omega_m^*\right| + \\ & + W_3\left|I_q - I_q^*\right| + W_4\left|V_{dc} - V_{dc}^*\right| \end{aligned}\ , \qquad (1)$$

where T is the average time, while 100 and 6 are the iterations' number and agents, respectively. W_1, W_2, W_3, and W_4 are used to compute the cost of control, which is 4×10^5 in our studied case.

V. The FRT capability enhancement method

Figure 5 depicts the grid coding necessities of some pioneer countries in the wind energy sector in the event of a failure [24, 25]. The graph indicates that, in an abnormal

Table 1. Gains of the PI controllers with GWO.

Technique	K_{p1}	K_{p2}	K_{i1}	K_{i2}
PI-GWO	2.932	2.932	199.2438	199.2438

Table 2. Indian grid code requirement.

Nominal grid voltage	Clearing time	V_{pf}	V_f
400 kV	100 ms	360 kV	60 kV
220 kV	160 ms	200 kV	33 kV
132 kV	160 ms	120 kV	19.8 kV
110 kV	160 ms	96.25 kV	16.5 kV
66 kV	300 ms	60 kV	9.9 kV

Table 3. BCS parameters.

Resistance value	1.5 Ω
Rated power	12 kW
Maximum temperature	150 °C
Thermal time constant	4 min
Weight	30 kg
Dimensions	(750.330.150) mm

Table 4. Parameters for simulated WECS [26].

Component	Parameter	Symbol	Value
WT	Blade radius	R	33.05 m
	Rated wind speed	v_W	12 m/s
	Optimal power coefficient	C_P	0.44
	Optimal tip speed ratio	λ_{opt}	10.5
	Wind density	ρ	1.225 kg/m^3
PMSG	Rated power	P	1.5 MW
	Rated stator voltage	V	575 V
	Pole pairs	p	40
	Generator stator resistance	R_s	0.01 pu
	Generator inductance in the d frame	L_d	0.7 pu
	Generator inductance in the q frame	L_q	0.7 pu
	Permanent magnet flux	ψ_{pm}	0.9 pu
BTB power converter	MSC frequency switching	$F_{sw\text{-}MSC}$	1 650 Hz
	GSC frequency switching	$F_{sw\text{-}GSC}$	1 650 Hz
	DC-Link voltage	V_{DC}	1 150 V
	DC-Link capacitor	C_{DC}	10 000 µF
	Grid frequency	F	60 Hz
LC Filter	Inverter side inductance	L_i	0.3 pu
	Inverter side resistance	R_i	0.003 pu
	Filter capacitor	C_f	0.0267 pu
	Damping resistance	R_d	0.003 pu

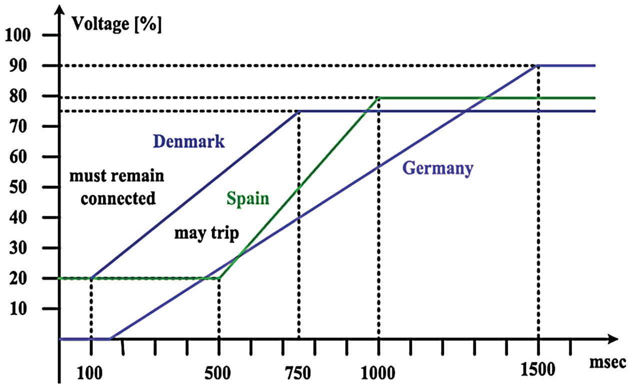


Fig. 5. FRT curve of grid code's pioneer nations in wind markets.

situation, the WT should be connected to the power grid for a known time according to each nation grid code, which fosters grid reliability. The fault clearing period, nominal system voltages, and fault clearing durations of the Indian grid code are all shown in Table 2. The V_f indicates that under a fault state, 15 percent of the nominal system voltage should be maintained, while the V_{pf} indicates the lowest voltage during normal wind system functioning. This paper investigates a simple cost-effective FRT capability enhancement method, namely a BCS, to get rid of surplus power at the DC bus and keep it in allowable ranges. Figure 6 shows a grid-connected PMSG including a BCS at the DC link. The used BCS parameters are listed in Table 3.

VI. Simulated results and discussion

MATLAB 2017b is used to evaluate the impact of the studied optimized controller on the performance of a grid-connected 1.5 MW PMSG-based wind system. The transient behaviors of the PMSG-based grid-connected system are investigated under symmetrical grid fault and step change of wind speed scenarios. The studied WECS parameters are listed in Table 4, and the used BCS parameters are given in Table 3.

Case 1: System performance as a result of step-change in wind speed.

In this case, PMSG with optimized controllers is tested under a step change of wind speed in the presence of an OTC technique to test the system's ability to realize MPPT.

A. WT performance

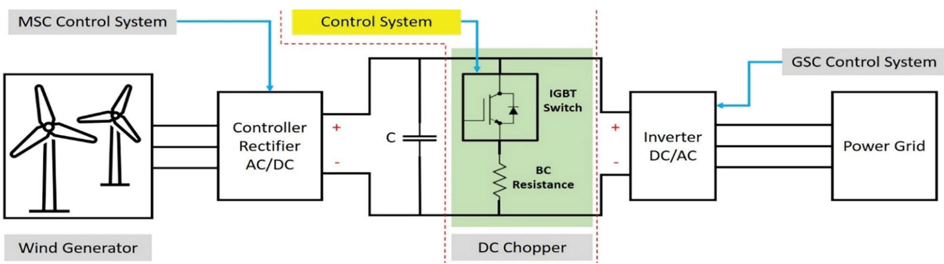
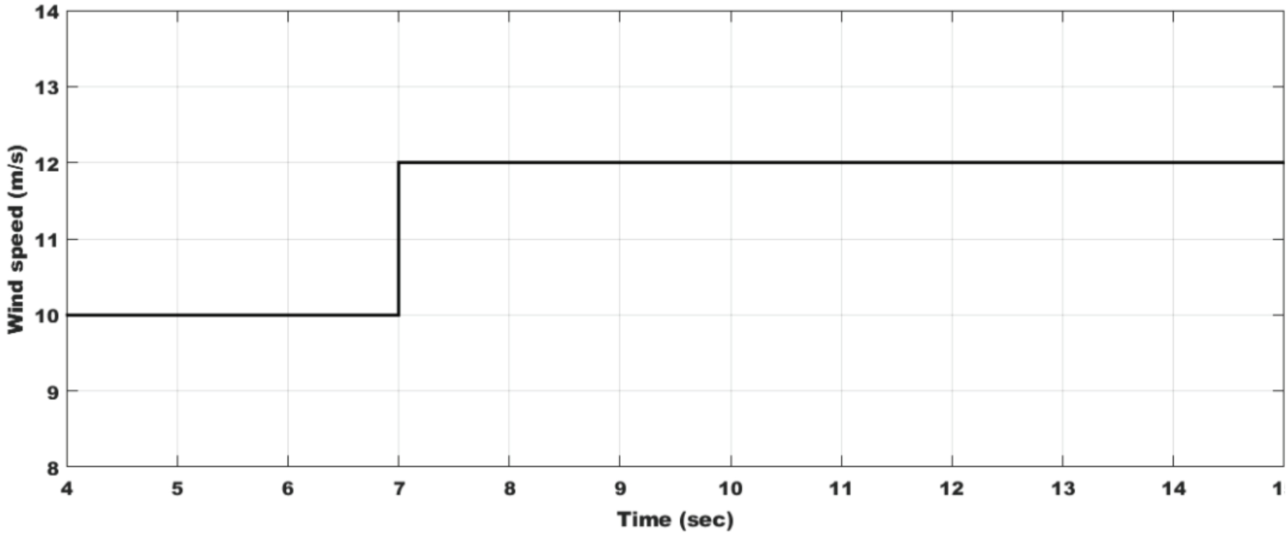
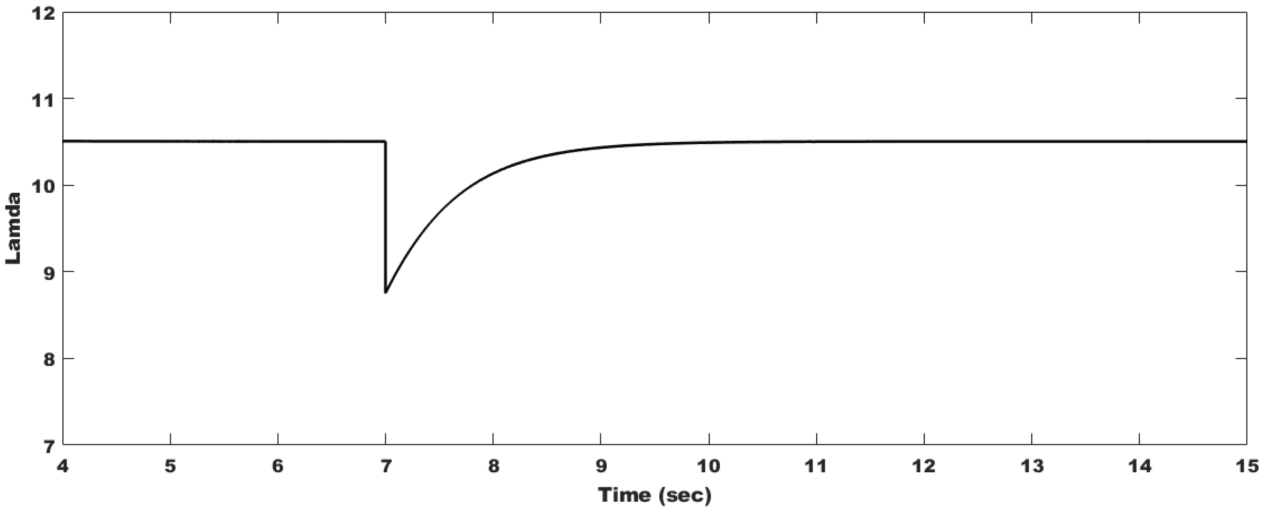


Fig. 6. BCS at the DC bus for grid-connected PMSG.



(a)



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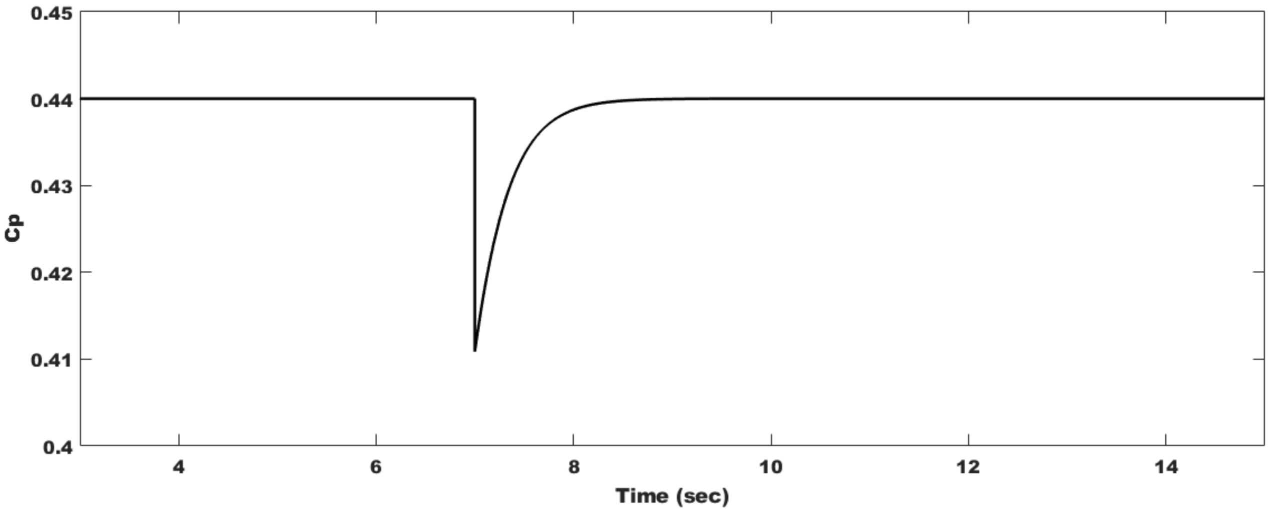
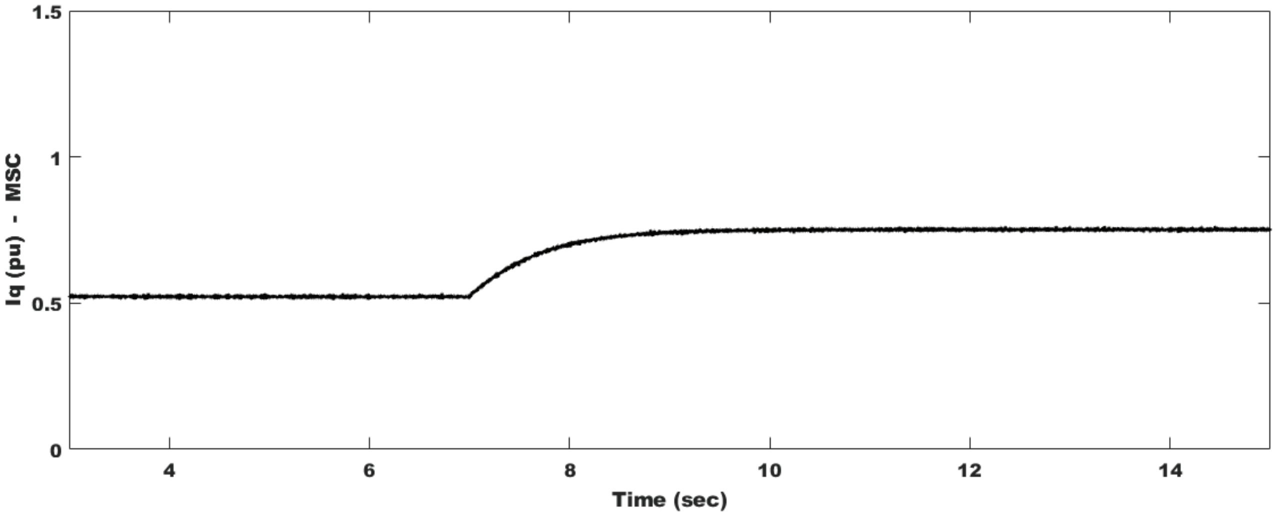
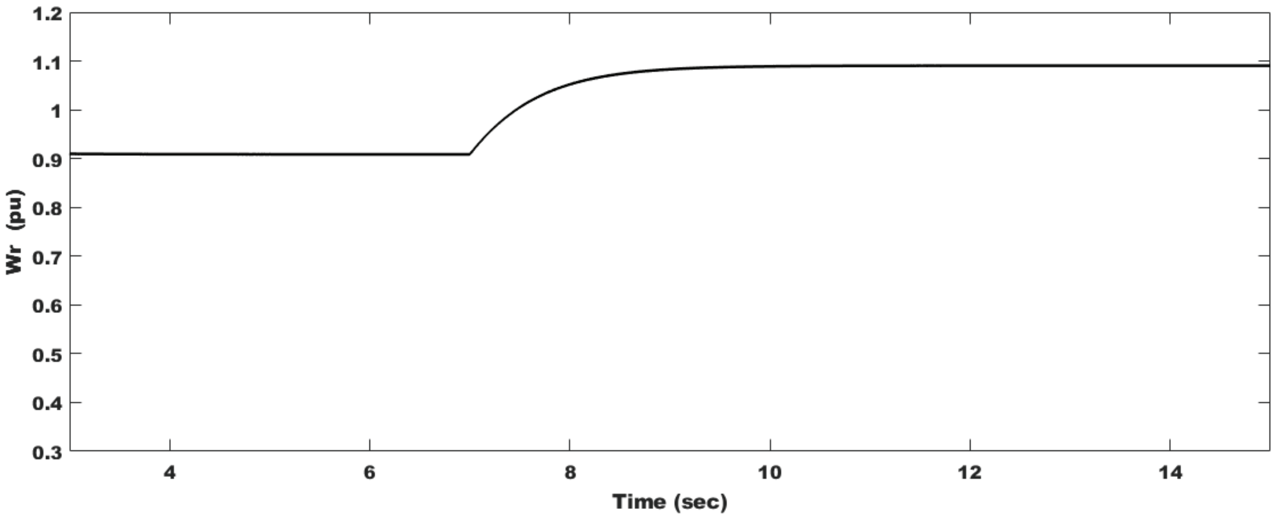


Fig. 7. WT performance: (a) wind speed profile, (b) λ, (c) C_P.



(a)



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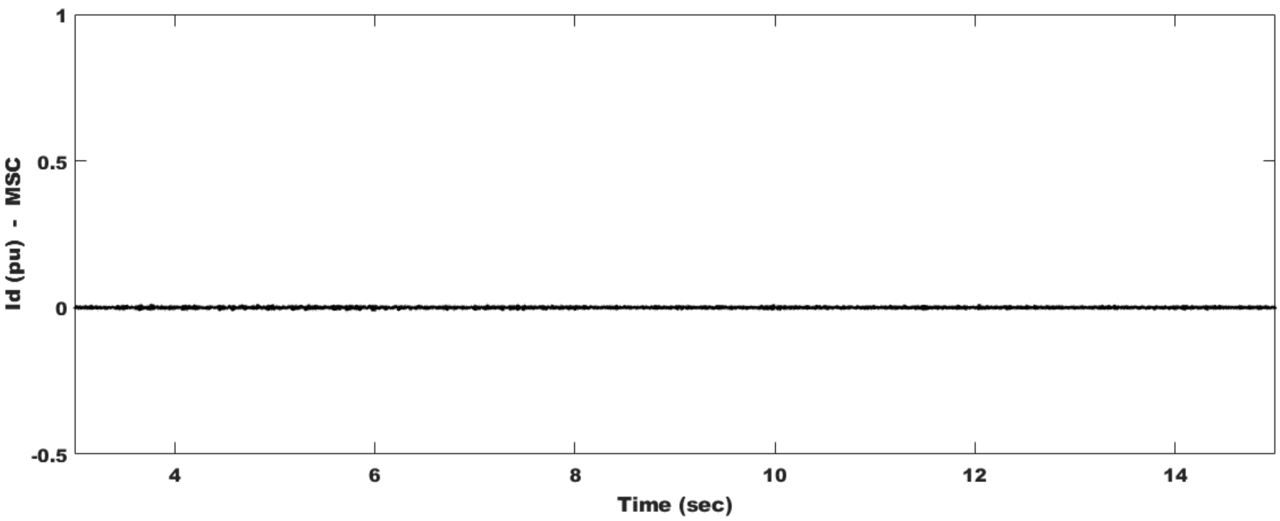
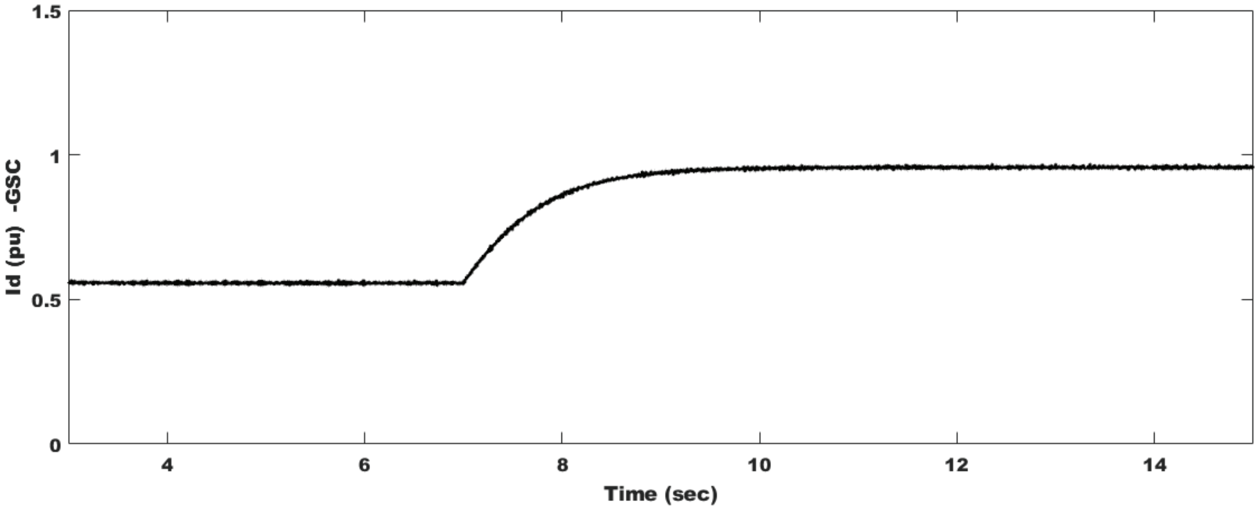
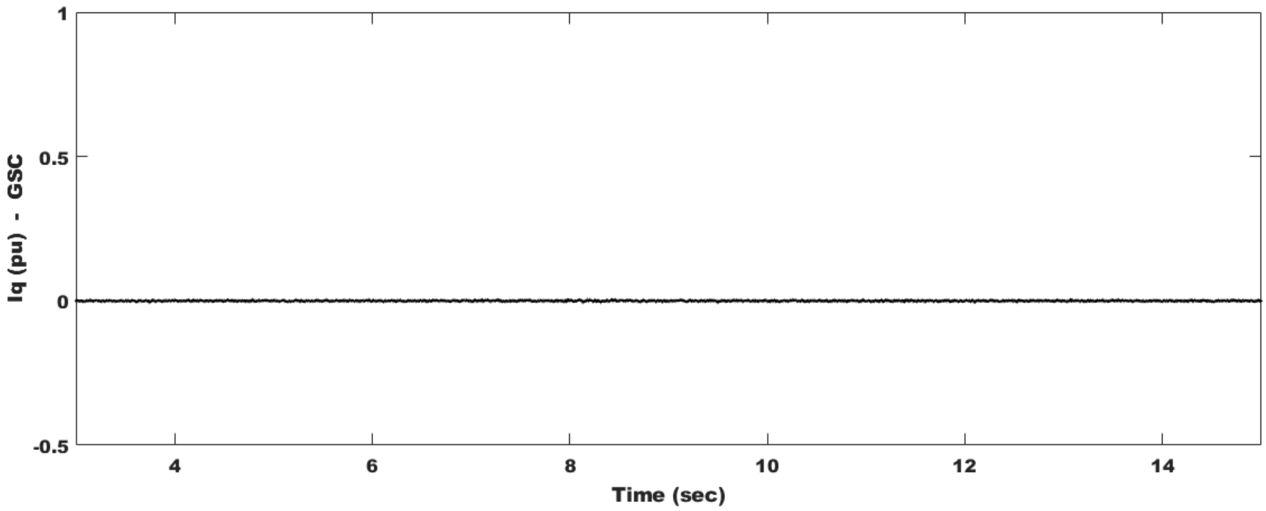


(c)

Fig. 8. MSC performance: (a) I_q-MSC, (b) ω_r, (c) I_d-MSC.



(a)



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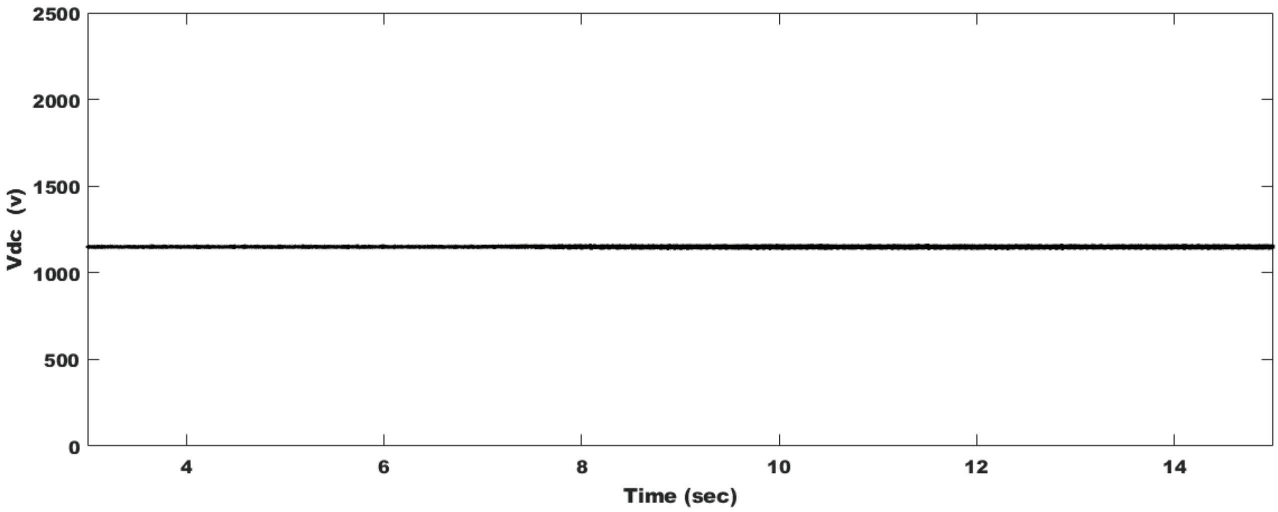
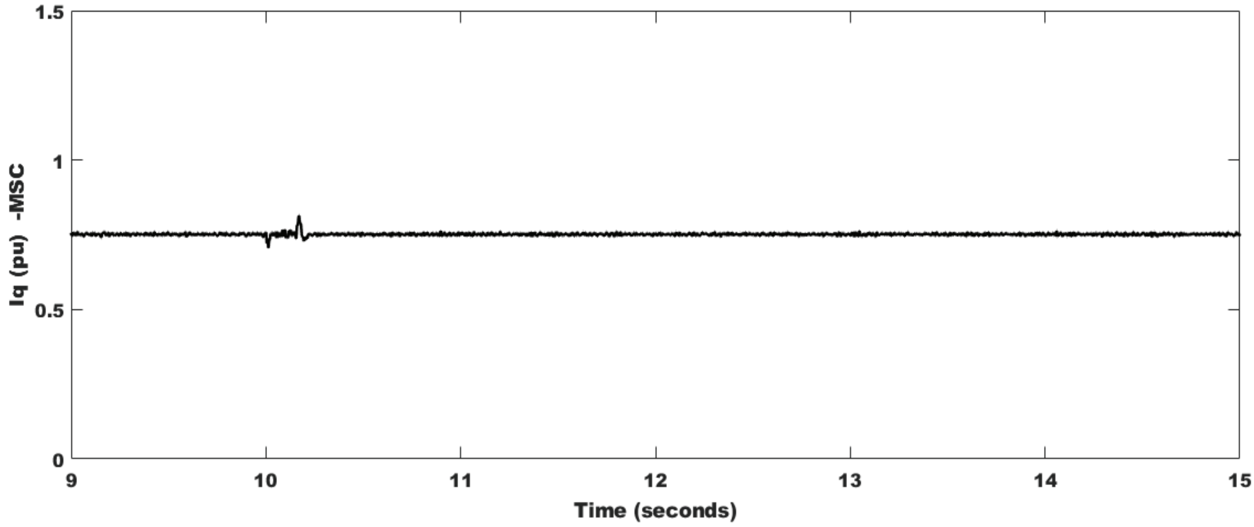
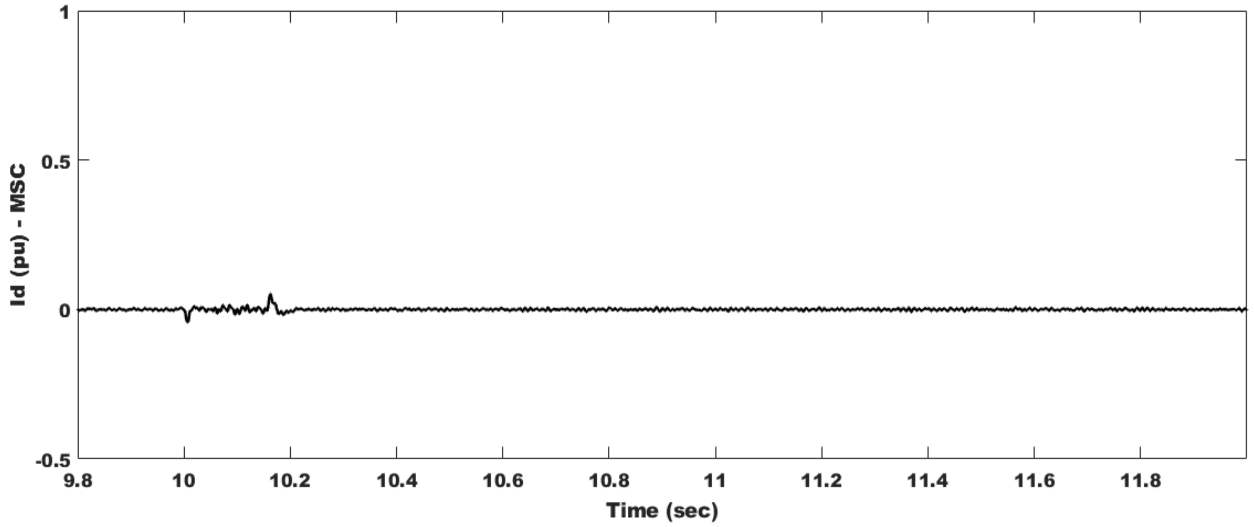


(c)

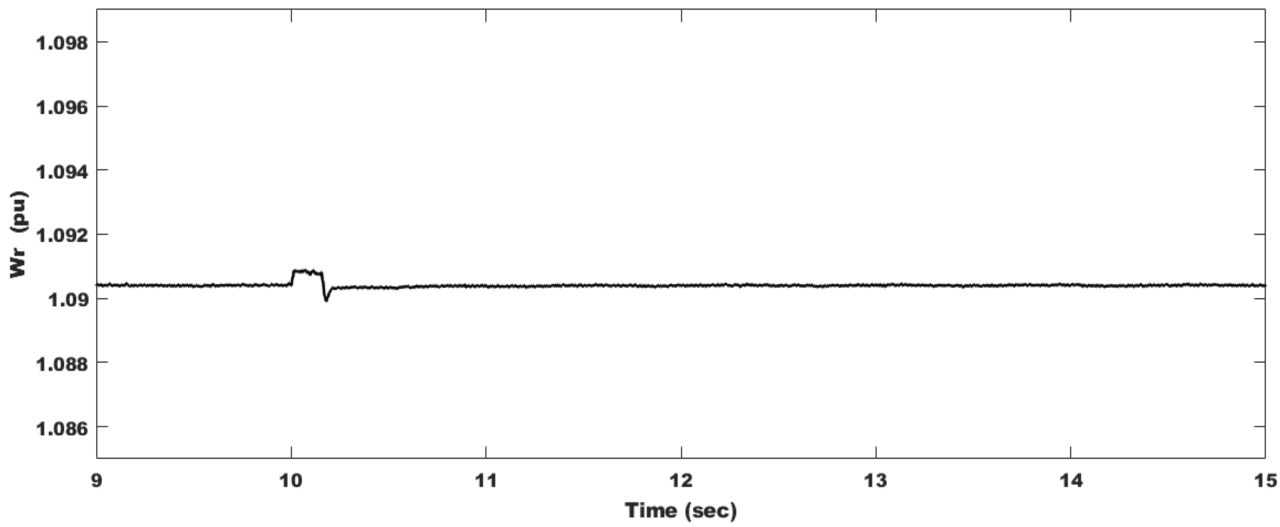
Fig. 9. GSC performance: (a) I_d-GSC, (b) I_q-GSC, (c) V_{DC}.



(a)



(b)



(c)

Fig. 10. MSC performance: (a) I_q-MSC, (b) I_d-MSC, (c) ω_r.

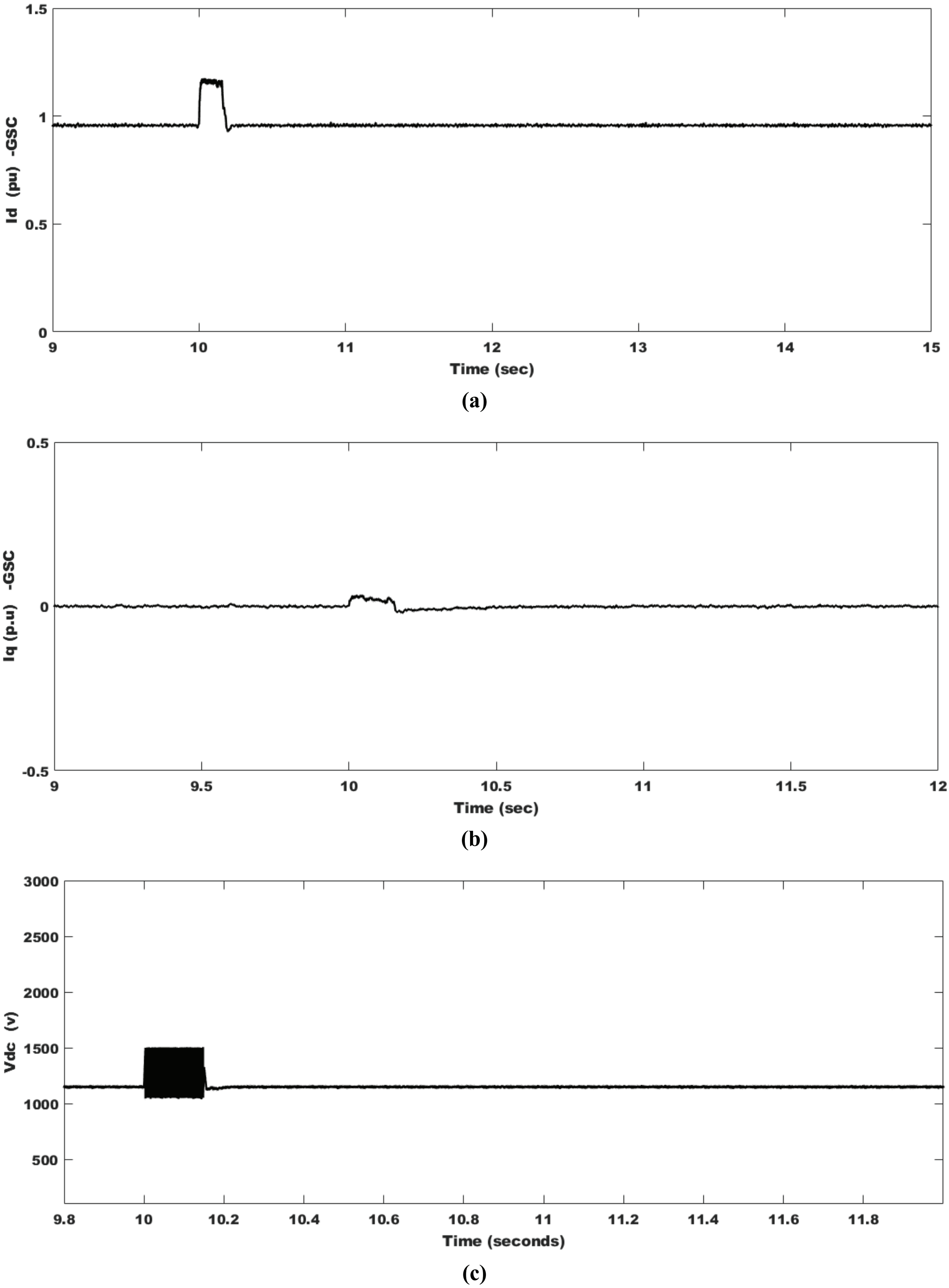


Fig. 11. GSC performance: (a) I_d-GSC, (b) I_q-GSC, (c) V_{DC}.

Figure 7 shows the WT characteristics. A step change in the wind speed, with an average speed of 11 m/s, is studied to assess the proposed controller (Fig. 7(a)). Both λ and C_P, which ensure operation at optimal values (10.5 and 0.44), are presented in Figures 7(b) and 7(c). With the optimized controller, the system reaches the optimal values rapidly, in 0.987 seconds roughly.

B. MSC performance

Figures 8(a) and 8(b) demonstrate that when the wind speed increases the MSC quadrature current and electrical angular speed rise. With the optimized controller, the system tracks the reference values rapidly, in 1.427 seconds roughly. Figure 8(c) shows that the MSC direct current is set to zero for maximal torque production and high efficiency.

C. GSC performance

Figure 9(a) demonstrates that GSC direct current rises when the wind speed increases. With the optimized controller, the system tracks the reference values rapidly, in 1.847 seconds roughly. The GSC quadrature current (Fig. 9(b)) is zero due to the unity power factor operation. Figure 9(c) shows that the V_{DC} is maintained constant because of the GSC controller's capabilities, which indicates that all the generated power is transferred from MSC to GSC.

Case 2: System performance as a result of a 3-phase fault.

In this case, PMSG with optimized controllers is subjected to a three-phase fault in the presence of a BCS to test the system's ability to realize FRT.

A. MSC performance

As seen in Figure 10, combining the GWO and BCS during the fault time suppresses transient oscillations in the system parameters, thereby increasing the PMSG's FRT capability. Figures 10(a) and 10(b) show small oscillations in MSC quadrature current and MSC direct current, respectively. These oscillations are below 2%, which reflects the role of the optimized controller. Figure 10(c) shows an increase in ω due to the voltage dip, where the system tries to supply the fault.

B. GSC performance

Figures 11(a) and 11(b) show GSC direct current and GSC quadrature current increase during the dip in grid voltage to maintain constant injected active power. These Figures also indicate very few oscillations in I_d and I_q of GSC. The reactive current rises during the fault to support the grid voltage (Fig. 11(b)). Figure 11(c) points out a small overvoltage in V_{DC} (a 30.4 % over-voltage during the fault period), and the system reaches its steady-state value (1150 V) after the fault is cleared.

VII. Conclusion

In this study, the dynamic performance of the PMSG-based WT system is enhanced by using the GWO approach. The clear benefits of the suggested technique (optimized MSC controllers) are efficient MPPT extraction, FRT capability improvement, decreased overshoot/undershoot performance, and smooth steady-state performance. The power and control circuits in MATLAB are used to implement the mathematical model of the addressed system. The response of PMSG's parameters is presented for two scenarios (a step change in wind speed and three-phase fault) to assess the robustness of the GWO technique and findings suggest that it was successful in achieving the FRT and MPPT objectives. The performance of WT, MSC, and GSC is studied during the wind speed changes and the investigated fault, and the parameters are shown to track their reference values rapidly. In the end, it can be stated that a GWO-based PI controller used at MSC enables greater PMSG penetration in modern power systems.

Conflict of interest:

The authors declare that they have no conflict of interest.

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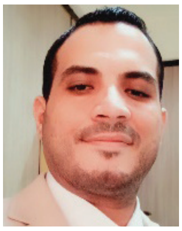

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