



Investigation of Dynamic Modes of Smart Technology-Based Distribution Electric Networks

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Abstract. As it is known, the development of modern intelligent power systems is based on the implementation of Smart Grid technologies at all stages of electricity generation, transmission, distribution, and consumption. In this context, distribution electric networks have particular importance. In the presented study, the main principles of the Smart Grid concept, modern intelligent technical means, and the key features of their application have been examined, and corresponding infrastructure schemes have been provided. Based on simulation modeling, the results of computational experiments for both steady-state and dynamic operating modes of conventional and Smart Grid-based distribution networks have been presented and analyzed. The obtained results confirm the main advantages of Smart Grid-based networks.

Keywords: power systems, distribution electric networks, Smart Grid technologies, steady-state and dynamic modes, FACTS devices, renewable energy sources, energy storage system.

1 Introduction

Modern power systems are currently in an active phase of digitalization and the implementation of intelligent technologies. The Smart Grid concept envisions the creation of intelligent distribution electric networks that can adapt to load variations, integrate distributed generation sources based on solar and wind power plants, incorporate energy storage systems, enable bidirectional power flow exchange, and provide consumers with new opportunities for managing their electricity demand [1–3].

In the present study, practical issues related to the investigation of the dynamic operating modes of equipment during transient and emergency processes are addressed through the synergistic combination of new control principles and approaches based on Smart technologies with modern high-speed electronics, data acquisition, and processing systems. It is noted that these technologies transform consumers into active participants in the energy process, allowing flexible and interactive control of energy consumption and distribution. At the same time, through the application of green technologies, the integration of energy storage systems into the grid is justified as an

important factor in enhancing the stability and resilience of the power system. Furthermore, the study evaluates the potential for applying Smart Grid technologies to improve the efficiency of distribution networks. The implementation of modern approaches not only increases network reliability but also provides strategic significance for energy security and economic sustainability.

The achievements of leading countries in the field of electric power engineering regarding the implementation of Smart Grid technologies are noteworthy [5,6]. According to the European Commission, which is developing a technological platform in the energy sector, Smart Grids can be characterized by the following key directions: Flexibility – the grid should adapt to the needs of electricity consumers; Accessibility – the grid should be open to new users; Reliability – the grid should ensure the security and quality of power supply in accordance with the requirements of the digital era; Profitability – the construction of an intelligent grid should deliver the greatest value through efficient operation, regulation, and the introduction of innovative technologies.

It should be noted that, along with these advantages, the application of Smart technologies is also associated with certain challenges such as the high cost of grid modernization, the need for standardization of data exchange protocols, cybersecurity and protection against cyberattacks, synchronization of distributed generation with the main grid, and the persistence of “obsolete infrastructure” in some regions [7–10]. Taking these aspects into account, this paper presents the results of a systematic analysis of theoretical and practical issues concerning the enhancement of reliability and efficiency of distribution electric networks under dynamic operating conditions through the application of Smart technologies.

2 Sample Evaluation of Distribution Network Parameters under Dynamic Modes Using Smart Technologies

For the purpose of evaluating the parameters of distribution networks under dynamic fault conditions with the application of Smart Grid technologies, the relationships of power balance, power flows, and the variation patterns of current and voltage are used. The corresponding expressions for the evaluation of these parameters are presented below.

Smart Grid technologies must continuously ensure real-time balance within the generation–load–storage system of the distribution network. The balance condition can be expressed as follows:

$$\sum P_{Gen}(t) + P_{BEM}(t) + P_{Sax}(t) = \sum P_{Yük}(t) + P_{Itki}(t) \quad (1)$$

Here, P_{Gen} – conventional generation capacity; P_{BEM} – generation from renewable sources; P_{Top} – energy storage capacity; $P_{Yük}$ – total demand power; P_{Itki} – network losses.

Smart Grid technologies utilize computational methods for network management; for example, the Newton-Raphson method can be applied to determine active and reactive powers at network nodes:

$$\left. \begin{aligned} P_i &= \sum_{j=1}^n |U_i| \cdot |U_j| \cdot Y_{ij} \cdot \cos(\theta_{ij} - \delta_i + \delta_j) \\ Q_i &= \sum_{j=1}^n |U_i| \cdot |U_j| \cdot Y_{ij} \cdot \sin(\theta_{ij} - \delta_i + \delta_j) \end{aligned} \right\} \quad (2)$$

Here, P_i, Q_i – active and reactive powers at the nodes; $|U_i|, |U_j|$ – voltage magnitudes at nodes i and j ; Y_{ij} – admittance between nodes i and j of the distribution network; δ_i, δ_j – voltage phase angles at nodes i and j .

One of the key features that Smart Grid technologies provide to the distribution network is the management of electricity demand. The Smart Grid participates in regulating the load depending on its price [12]:

$$P_{Yük} = P_o(t) - \alpha \cdot \Delta C(t) \quad (3)$$

Here $P_o(t)$ – base load; $\Delta C(t)$ – tariff change; α – demand flexibility factor.

In addition to the above, the study presents the results of investigating the dynamic operating modes of Smart Grid-based distribution networks during faults (short circuits) and examines the potential applications of these technologies in network operation management.

3 Impact of Smart Grid Technologies on the Energy Efficiency of Distribution Networks under Dynamic Modes

In modern power systems, the energy efficiency and sustainable development of Smart Grid-based distribution networks are among the main priorities. Such networks are generally defined as medium- and low-voltage systems with distributed generation sources, energy storage, and controllable loads. The infrastructure scheme of this type of network is shown in Figure 1 [9,13].

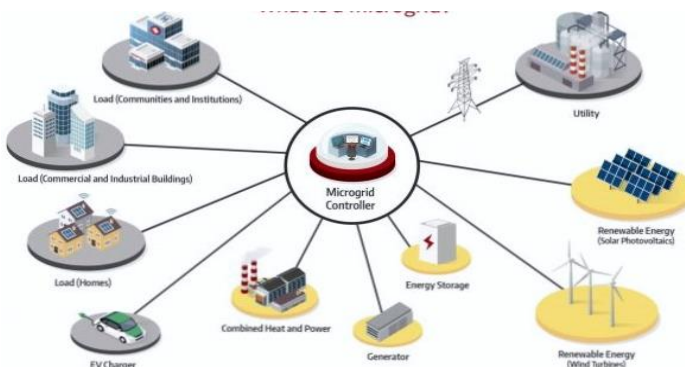


Fig. 1. Infrastructure Scheme of a Smart Grid-Based Network

An important feature of Smart Grid-based networks is that, while operating within the energy distribution system, they can automatically switch to an isolated mode during faults and, after the fault is cleared, restore synchronization with the main grid while maintaining the required power quality.

In the future, it is envisaged that the operation of the power system will be carried out through close interaction between centralized and decentralized distributed generation sources. Distributed generators can be integrated into microgrids or “virtual” power plants [14].

Electricity from microgrids will be directed to consumers or back to the regional grid depending on demand and supply conditions. Real-time monitoring and control will ensure continuous data exchange, allowing consumers to adjust their electricity supply according to their needs.

4 Role of Smart Grid Technological Tools in the Management of Distribution Networks under Dynamic Modes

The application of innovative components and devices in distribution electric networks is based on the latest scientific and technological achievements in fields such as superconductivity, power electronics, energy storage systems, and diagnostics. Examples of these technologies include Flexible Alternative Current Transmission System (FACTS) devices, high-voltage direct current transmission systems, superconductors, smart devices, modern semiconductor-based power electronics, and renewable energy sources [15].

The main elements of FACTS devices are high-power automated units. Each of these devices can be used both individually and in interaction with other devices to control the parameters of electric power systems.

The essence of FACTS technology is that the electrical network transforms from a passive device for power transmission into a device actively participating in the control of the operational modes of electric networks. First-generation FACTS devices (FACTS-1) are devices that provide voltage (reactive power) regulation and ensure the necessary reactive power compensation in electrical networks (static reactive power compensator, thyristor-controlled reactor, thyristor-switched capacitor, phase-shifting transformer, etc.), while second-generation FACTS-2 devices are devices based entirely on fully controllable power electronic devices (IGBT transistors, IGCT thyristors, etc.) [16].

FACTS-2 has a new regulation quality – the vector, not only the magnitude but also the phase of the voltage vector of the electric network is regulated (synchronous static compensator (STATCOM), reactive power synchronous static compensator based on voltage converter, unified power flow controller, synchronized synchronous compensator, including with a rotating shaft, synchronized synchronous electromechanical frequency converter, phase-shifting transformer).

In addition, the main elements of Smart technologies can include the following [17]: Smart metering – intelligent measurement devices; SCADA and TP AIS – automated control systems for technological processes; energy storage systems

(batteries, supercapacitors, pumped-storage plants); electric vehicles as part of the network (Vehicle-to-Grid); ICT infrastructure – IoT, 5G/6G, cloud computing, and artificial intelligence [18].

The mentioned Smart tools play a significant role in regulating and managing the operational modes of distribution networks during faults (short circuits), making their application necessary

5 Application of Intelligent Energy Metering Systems in Dynamic Modes

Intelligent electricity metering systems (smart meters) are an integral part of Smart Grid technologies. The smart metering system technology enables the transition from centralized generation to distributed generation and allows the transmission of electricity through two-way communication with electricity meters: data reading, remote connection/disconnection, power limitation, tariff changes, and monitoring and recording of fault events.

The smart energy metering system (see Fig. 2) involves the installation of intelligent measurement devices on the consumer side, their regular interrogation, data processing, and provision of information on electricity consumption. The main components of a smart energy metering system include end-user devices (EUC) with digital interfaces or built-in communication modules (PLC, RF, GSM, GPRS, 2G–4G, FOCL), data collection and transmission devices, GPRS modems, and hardware and software systems.

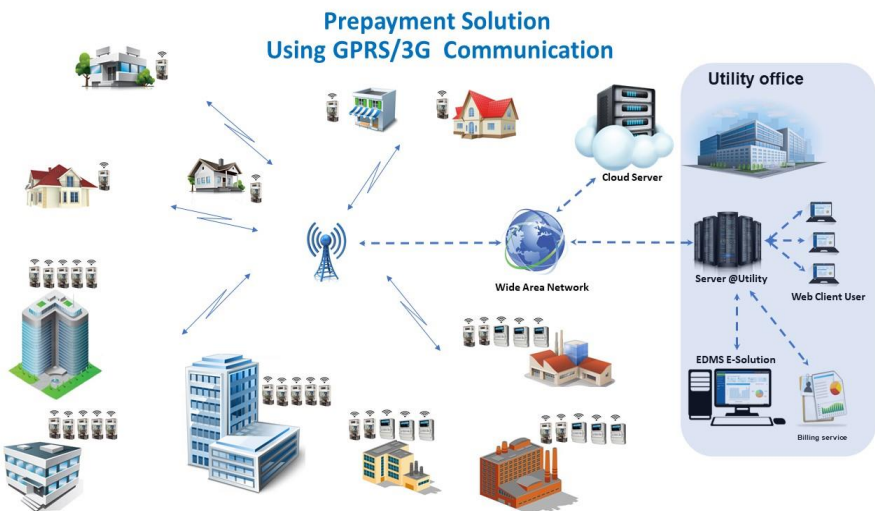


Fig.2. Structural Diagram of the Smart Energy Metering System

The installation of smart energy metering devices relieves the consumer from the monthly obligation of collecting information on consumed electric energy and transmitting it to the electricity supply company. Moreover, each subscriber can

analyze their data in a personal account via the website or mobile application. Indicators for every day and hour are available for analysis, allowing the subscriber to optimize the energy consumption schedule and, accordingly, select an individual tariff plan based on the time of day, thereby reducing costs.

In addition, smart metering systems allow the recording of voltage and frequency levels at the connection point, as well as indicators of voltage non-sinusoidality and asymmetry, in order to analyze the quality of supplied electric energy. Protective functions can also be implemented in energy metering devices so that the subscriber is disconnected from the external network in case of operating regime violations.

The implementation of an intelligent metering system has the following advantages: ensuring accurate measurement of consumed energy resources; automated and operational processing, transmission, and display of consumption volumes; monitoring of consumption patterns; formation of balance across meter groups and comparison of data to detect unauthorized connections; obtaining information about actual losses in electrical networks; the ability to remotely limit or disconnect electricity consumption; evaluating the effectiveness of measures aimed at saving electric energy; controlling power flows; recording, storing, and communicating changes in operating parameters during emergency situations.

The above-mentioned features and capabilities of the intelligent energy metering system confirm its importance for managing the operating modes of distribution electrical networks under dynamic conditions. Therefore, the application of intelligent energy metering systems in ensuring the stable operation of the network under short-circuit conditions is one of the essential components in creating modern intelligent power systems.

6 Simulation Modeling of Dynamic Modes of Distribution Networks

6.1 Simulink Model of a Distribution Network

For the purpose of analyzing the operational efficiency of an existing and SmartGrid-equipped distribution electrical network under dynamic conditions (during short-circuit events), simulation modeling was carried out using the Simulink software at voltages of 6/0.4 kV and 35/0.4 kV. The simulation scheme is shown in Figure 3. As seen from Figure 3, both in the existing and transformed networks, a 12 MW wind power plant and a 10 MW solar power plant are considered.

From the Simulink model of the distribution network, it can be seen that the renewable energy sources and the system at 35 kV voltage are subsequently connected to consumers through a 6/0.4 kV distribution transformer. The 35/0.4 kV distribution network equipped with SmartGrid technologies, however, is connected to the system via 35 kV voltage lines and supplies electricity to consumers directly through a 35/0.4 kV distribution transformer, without the need for a 6/0.4 kV transformer.

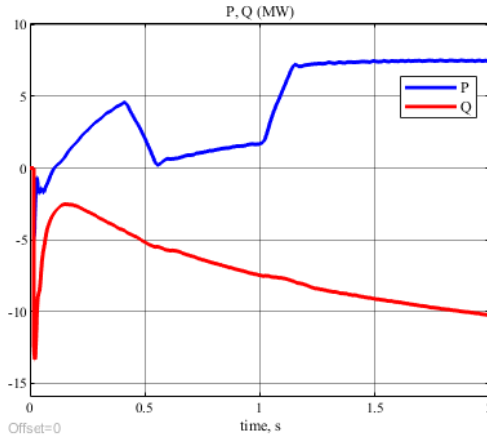


Fig.4. Active and Reactive Power Variation Diagrams for the Feeder Bus of the 6/0.4 kV Distribution Network

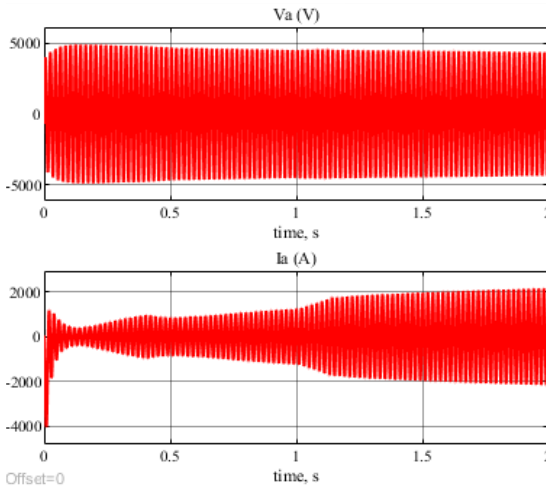


Fig. 5. Voltage and Current Variation Curves for the Feeder Bus of the 6/0.4 kV Distribution Network

As seen from Figures 4 and 5, in response to variations in wind and solar radiation, the operating parameters at the energy system bus adjust accordingly, and the regime stabilizes approximately after 1.2 seconds.

Figures 6 and 7 show the modeling results of the steady-state modes of the 35/0.4 kV distribution network. The simulation reports of the 35/0.4 kV distribution network equipped with SmartGrid technologies were performed based on the Simulink model of the distribution network shown in Figure 3. Figure 6 illustrates the variation curves of active and reactive power in the steady-state mode, while Figure 7 shows the voltage and current variation curves.

As seen in Figure 6, after the active power supplied from the system buses stabilizes at approximately 0.1 s, it increases to 5 MW at 0.4 s, decreases to 1 MW over a period of 0.08 s, and remains at this level between 0.55–1 s. At 1 s, it rises again to a level of

9 MW and stabilizes at this value. The reactive power, after a transition period of 0.12 s, stabilizes at 5 MVar in the opposite direction. The reactive power required by the network is provided through the STATCOM device.

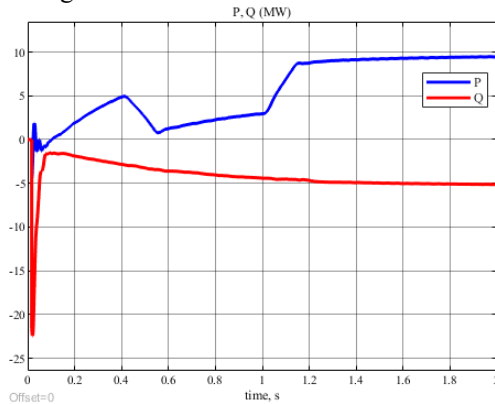


Fig. 6. Simulation Curves of Active and Reactive Power at the System Bus of the 35/0.4 kV Distribution Network Equipped with SmartGrid Technologies

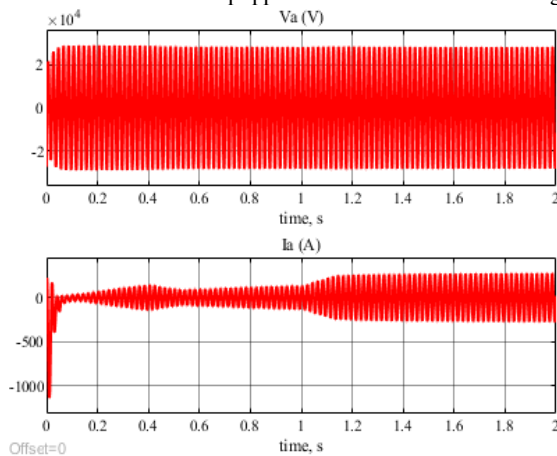


Fig. 7. Simulation Curves of Voltage and Current at the System Bus of the 35/0.4 kV Distribution Network Equipped with SmartGrid Technologies

6.3 Simulation Modeling Results of Fault (Short-Circuit) Modes of Distribution Networks

Process in distribution networks is short-circuiting. Its main effects include overloading of equipment, overheating and breakdown of insulation, line failures, and increased voltage dips at consumers. Therefore, the study of short-circuit modes is an essential stage in the design, operation, and development of distribution electrical networks, including those equipped with modern SmartGrid technologies.

The study of short-circuit modes is traditionally relevant for the selection of electrical equipment, setting protection parameters, ensuring the reliability of power supply, and solving other related tasks. In SmartGrid-equipped networks, however, the

analysis of these modes has its own specific features. SmartGrid technologies introduce new factors that make short-circuit analysis even more relevant. These factors include:

1. **Decentralized generation** (solar power plants, wind farms, microturbines, energy storage devices). Energy sources are distributed across the network and can contribute additional current during short-circuit events. At the same time, the variability and uncertainty of generation (e.g., wind, solar) make short-circuit prediction considerably more complex.
2. **Bidirectional power flows.** Unlike classical radial networks, in SmartGrid-equipped networks, power can flow both from the supply center to consumers and from distributed sources back into the network. This complicates the calculation of protection selectivity and setting parameters.
3. **Use of intelligent devices** (IEDs, smart switches). This requires accurate modeling of short-circuit currents for automatic adaptation of settings and coordination with other network elements.
4. **New network operating modes.** A SmartGrid network can operate in “islanded” (autonomous) mode or connected mode. Short-circuit currents differ significantly in these modes, which must be considered in protection design.

Thus, the main objectives of studying short-circuit modes in SmartGrid-equipped networks are: increasing the safety of personnel and equipment, ensuring correct operation of protection and automation during network regime changes, optimizing relay protection settings with consideration of distributed generation, forecasting fault consequences, improving the reliability of consumer power supply, minimizing damage through rapid fault localization, and integrating renewable energy sources without loss of network stability and selectivity.

Guided by these objectives, the study of short-circuit modes was carried out for the considered distribution networks under both SmartGrid-equipped and non-SmartGrid conditions.

To investigate the comparative performance of existing and transformed SmartGrid-equipped distribution networks, the variations of network operating parameters during a three-phase short-circuit at the most heavily loaded bus were obtained using the Simulink model. The results of computational experiments for the 6/0.4 kV distribution network are presented in Figures 8–11, while the results for the transformed 35/0.4 kV distribution network are shown in Figures 12–15.

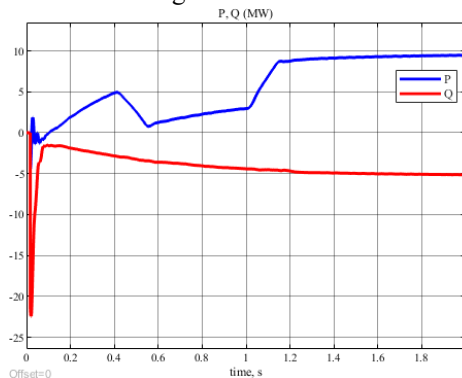


Fig. 8. Time Variation Diagrams of Active and Reactive Power at the Buses of the Solar Power Plant in the 6/0.4 kV Distribution Network for the Short-Circuit Transient Mode

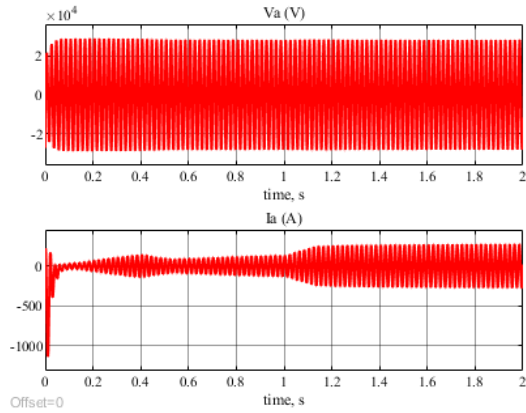


Fig. 9. Simulation Diagrams of Voltage and Current Variations at the Buses of the Solar Power Plant in the 6/0.4 kV Distribution Network for the Short-Circuit Transient Mode

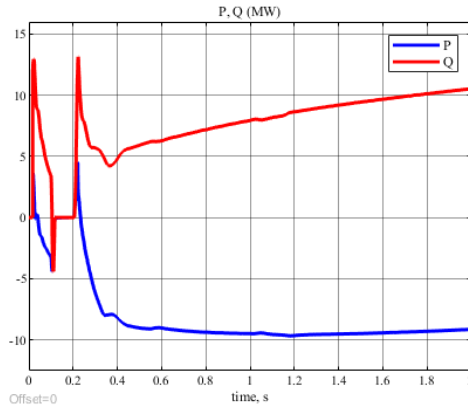


Fig. 10. Simulation Diagrams of Active and Reactive Power Variations at the Buses of the Wind Power Plant in the 6/0.4 kV Distribution Network during Short-Circuit Transient Mode

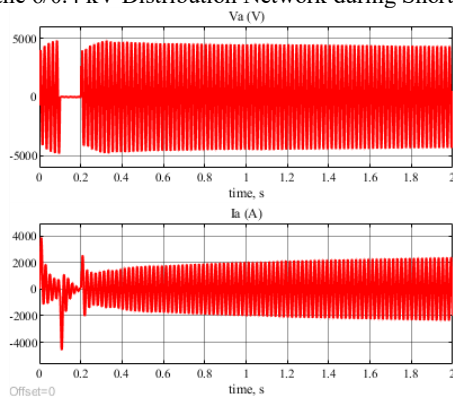


Fig. 11. Simulation Diagrams of Current and Voltage Variations at the Buses of the Wind Power Plant in the 6/0.4 kV Distribution Network during Short-Circuit Transient Mode

As can be seen from the simulation curves, the transient processes in the 6/0.4 kV distribution network last approximately 0.42 seconds, after which the post-fault steady-state regime is established. In the case of the 35/0.4 kV distribution network, the transient processes last about 0.2 seconds, which reflects the important features of Smart Grid technologies and once again confirms the relevance of developing such types of networks.

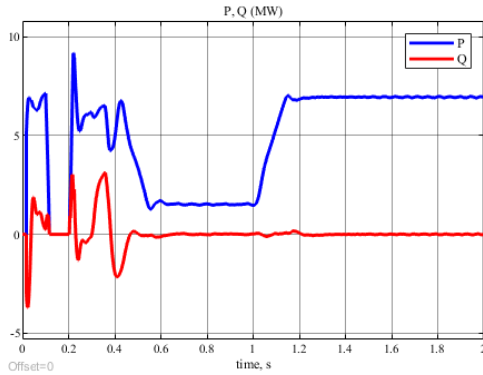


Fig. 12. Diagrams of active and reactive power variations at the busbars of the solar power plant during the short-circuit transient mode in the 35/0.4 kV distribution network

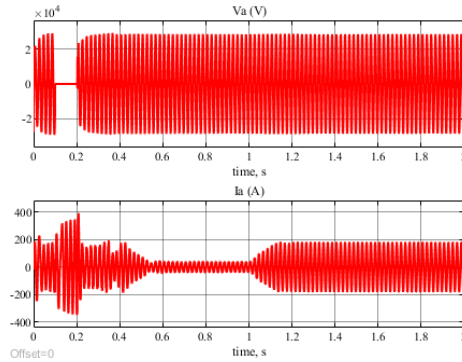


Fig. 13. Simulation diagrams of voltage and current variations at the busbars of the solar power plant during the short-circuit transient mode in the 35/0.4 kV distribution network

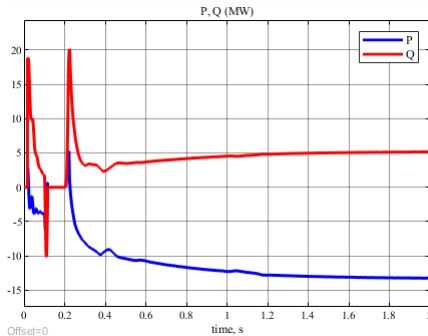


Fig. 14. Simulation diagrams of active and reactive power variations at the busbars of the wind power plant during the short-circuit transient mode in the 35/0.4 kV distribution network

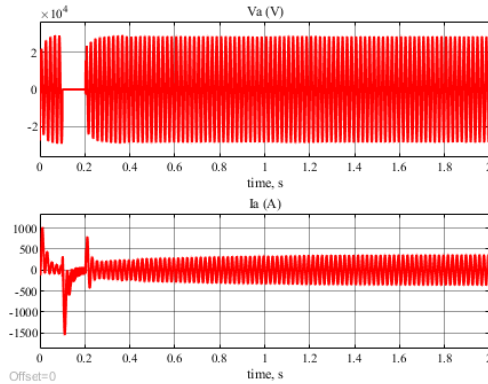


Fig. 15. Simulation diagrams of current and voltage variations at the busbars of the wind power plant during the short-circuit transient mode in the 35/0.4 kV distribution network

7 Conclusion

The specific features of implementing Smart Grid technologies in distribution power networks have been studied and analyzed. Based on the conducted analysis, the infrastructure schemes for the application of Smart Grid technologies and their main advantages have been presented.

To evaluate the efficiency of distribution power networks with Smart Grid technologies, computational experimental studies of dynamic modes under steady-state and fault conditions were carried out in Simulink modeling for both conventional networks and those integrated with wind and solar power plants. The obtained results show that the integration of distributed energy resources, maintenance of local energy balance, islanding capability during faults, and subsequent restoration of synchronous operation significantly enhance the stability and resilience of the network.

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