Development of technical requirements for generating units of distributed energy resources in the conditions of electric power systems transformation

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Abstract. The paper describes the prospects for commissioning distributed energy resources (DER) in Russia and considers the historical features, as well as the consequences of structural, qualitative, and quantitative changes in Russia's UES. The main short and long-term transformational changes, as well as current and future challenges, are described. The main changes in the circuit and operating conditions when integrating DERs into distribution grids in the mass scale are shown. The authors justify the need for making changes in the existing technical requirements for power equipment, relay protection, and automation instruments. Technical requirements for the distributed generation plants and new types of equipment (energy storage systems, devices with power converters, etc.) should be developed. The paper proposes a new approach to the development of the DER-based power distribution schemes considering the specifics of modern generating units and loads. It is noted that solving these issues will ensure reliable DER functioning as part of power systems.

1 Introduction

Over the past decade, one of the main trends in transforming electric power systems (EPS) in Russia and the world is the decentralization of generating facilities.

Decentralization means increasing the share of DERs of small unit capacity (from units of kW to tens of MW) in the structure of generating facilities integrated into the EPS. This is dictated by the need to meet the public demands in the necessary energy types in the required volumes and at affordable prices, as well as the reliable and safe power supply [1].

International experience shows that DERs are developed mainly due to the construction of facilities based on renewable energy sources (RES). According to forecasts, the RES share in power generation will globally increase to 27.1 % by 2030 and up to 48.8 % by 2050. In the RES structure in 2030, wind power will dominate (70 %), but by 2050, its share will be reduced to 47 % due to an increase in the share of solar power (cheaper high-performance photovoltaic modules) [2].

In Russia, until 2024, wind (WPP) and solar (SPP) power plants with a total installed capacity of 5.3 GW should be commissioned, while in some EPSs, the RES share will approach 15 %, which requires creating technical opportunities to control power supply modes.

Implementing DERs by household consumers is stimulated by Federal Law No. 471-FZ dated December 27, 2019, which defines the legal framework for the operation of micro-generation facilities and the procedure for the sale of generated power by their owners in the retail market.

In Russia, one of the important power industry development issues is its gradual intellectualization. The development and implementation of modern technologies should ensure improving the reliability, safety, and efficiency of control over the EPS modes, as specified in the Energy Strategy of Russia for the period up to 2035. The EPS transformation supposes the widespread use of DERs, energy storage systems, active consumers, and controlled devices with power converters integrated into the Smart Grid [3-5].

Under such conditions, the historical peculiarities, and the current situation in Russia's UES should be analyzed to determine approaches to future EPS development.

2 Historical peculiarities and current situation

The historical peculiarities of Russia's UES include:

– Insufficient transmission capability of bulk power (220-750 kV) and distribution grids (35-110 kV) in some cases,

– Significant power transmission line (PTL) length and branching 0.4 kV (up to 10 km) and 6-10 kV (up to 90 km) feeders, considering the branch lines,

– A large number of isolated remote power regions in the Far North and the Far East of the country,

– Low level of load redundancy and automation of 0.4-35 kV distribution grids (DERs, automatic transfer equipment, reclosers),

– Large-scale use of asynchronous automatic circuit

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reclosers (ACRs) in 35-110 kV grids,

– Widespread use of knockouts and short-circuiting switches in 35-110 kV grids,

– The use of isolated neutral in 6-35 kV grids,

– Widespread use of emergency control devices (automatic frequency load shedding, special load-shedding schemes) acting to disconnect consumers,

– The use of steam and hydraulic turbines with high mechanical inertia constant ($T_{j\ \mathrm{eq}} \approx 10$ s), mechanical safety margin, and thermal resistance,

– The use of main and redundant protection (short- and long-range redundancy) with long time delays in 6-110 kV grids.

It is important to note that Russia has territorial, climatic, and historical peculiarities associated with the existing power industry structure. Simple copying of international experience could be detrimental to the reliable functioning of Russia's UES, which was created based on different principles. Increasing DER share without a clear understanding of the goals and results may lead to the transfer of the burden of maintaining a centralized infrastructure to a narrower consumer composition and increased power costs.

Analysis of the current situation allows stating the facts to be considered when planning Russia's UES development:

– High level of wear and tear of generating and power grid equipment, especially in distribution grids,

– The regularity of selecting various parts of the EPSs located in the centralized power supply zone to the main operating mode,

– The widespread use of gas turbine (GTU) and combined cycle (CCGT) generating units (GUs) of foreign manufacturers with simultaneous decommissioning ineffective (moral and physical wear) steam turbine GUs at thermal power plants,

– The lack of reliable statistical data on the GTU and CCGT reliability indicators in Russia,

– Integration of large WPPs and SPPs into the 35-110 kV grid (increasing the RES share in the generating facility structure > 15 %),

– The growing number and severity of accidents in EPS, accompanied by significant damage to industrial consumers,

– Mass-scale implementing process lines of foreign manufacturers at industrial enterprises (high requirements for power quality indicators),

– The widespread DER construction, including microgeneration, with a total installed capacity of ≈ 17.5-18 GW.

The main consequences of structural, qualitative, and quantitative changes in Russia's UES in recent years are:

– Damage to the GUs associated with a reduced mechanical safety margin of parts and assemblies aimed at increasing the efficiency,

– Unnecessary GU shutdowns due to decreased resistance to thermal overloads, and as a result, reducing the mass-dimensional characteristics to lower the GU cost,

– Significant increase in the transient process rates under the conditions of the island operation mode of power regions [6],

– Deviation of power quality indicators due to stochastic power generation by RES facilities and mass-scale implementing devices with power converters [7],

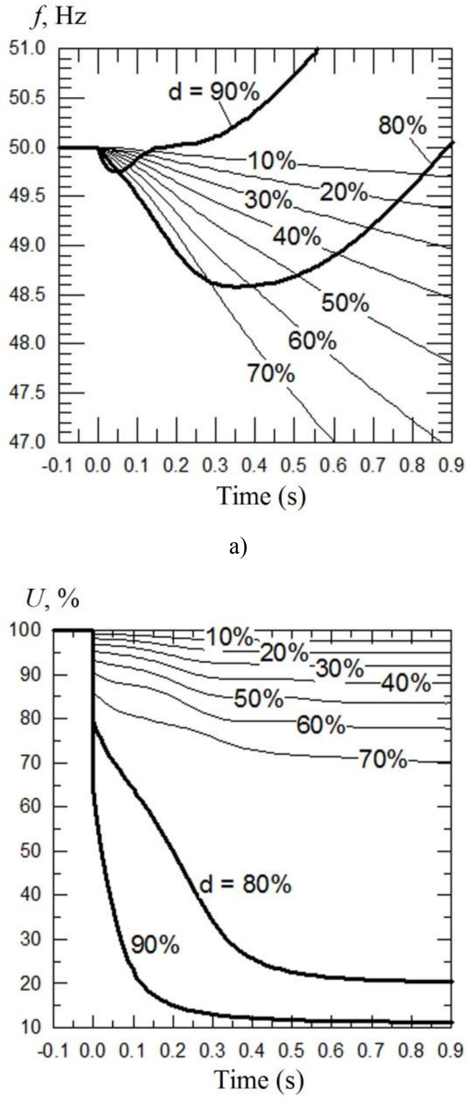
– The growing number of systemic and local accidents,

– An increasing voltage at the distribution grid nodes due to the mass-scale integrating micro-generation facilities [8],

– The emergence of multi-machine asynchronous modes in the grids under rated disturbances [9],

– A significant impact of load parameters on those of transient processes due to comparable total powers and low trans-resistances [10].

The consequences of separating a load node from an external network with different values of initial active power deficits are shown in Figure 1.



b)

Fig. 1. Consequences of various active power deficits (d): (a) – frequency deviation; (b) – voltage deviation.

Let us review main Russia's UES transformation areas and current and prospective challenges to be considered when developing new principles for building distribution grids.

3 EPS transformation, current and prospective challenges

The main short- and long-term EPS transformation areas include:

– Balanced development of local DER-based smart power systems integrated into Russia's UES to supply power to consumers during peak hours,

– Development of competition and long-term relations in the wholesale and retail power markets,

– Development of Smart Grids, automated trading platforms, consumer services, and the 'power Internet',

– Ensuring the cost-effective use of centralized and decentralized power and heat supply systems using local resources, including RESs,

– Development of domestic scientific and technical potential, creating and developing advanced technologies in the energy sector, including the RES ones, creating competence centers,

– Increasing the manufacture of competitive main and auxiliary DER equipment in Russia.

Current and prospective challenges include:

– Mass-scale development of microgeneration and further growth of the RES share in the generating facility structure,

– A lot of smart devices with own local control algorithms, causing continuous oscillation of the mode parameters,

– The complexity of implementing the centralized control algorithms, considering a large number of control objects and a corresponding increase in the problem dimensionality,

– Impossibility of manual control over modes in low and medium voltage distribution grids under the conditions of mass-scale DER integration, including energy storage systems,

– The need for a mass-scale reconstruction of 6-35 kV grids with a change in their design principles to implement Smart Grids projects and local smart power systems,

– It is required to combine the functions of relay protection (RP), anti-emergency (AE), and mode automation (MA) in multifunctional digital devices with the possibility to remotely change operation algorithms and settings [11, 12].

Given the above, the Russian power industry needs own scenario of development, combining the balanced participation of conventional power industry and DERs, considering the country's peculiarities, contributing to appropriate benefits for consumers and the economy of the regions and the entire country, and creating a demand for implementing innovative solutions.

An increase in the RES share in the generating facility structure leads to increasingly non-steady power generation, and control over modes under these conditions requires the use of global communication systems combining various software and hardware complexes. The need to continuously maintain a balance complicates the principles of controlling many different DERs.

4 New principles of building distribution grids

The new principles for building low- and medium-voltage distribution grids should be developed to ensure the possibility of free integration of different DERs. Guidelines for designing low-voltage (0.4 kV) and medium-voltage (6-35 kV) grids should also be developed. This is determined by the need to control grids as a single object: microgrids and multi-microgrids within 0.4 kV grids, and mini-grids within 6-35 kV ones.

Mini-grid (microgrid) is a local system integrating PTLs, substations, DERs (microgeneration), and power receivers of consumers, having fixed electrical boundaries, and functioning as a single control object when operating in parallel with an EPS or island mode, while ensuring the required power reliability and quality indicators.

When developing guidelines, the below principles and technical solutions should be used:

– The hexagonal structure of building 6-35 kV grids, if high structural reliability to supply power to essential consumers (as a rule, three branches run to the nodes) and the integration of mini-grids (DERs) are required,

– New substations should be built, and existing ones reconstructed considering the provision of separate power supply (from different cells) to the critical (I and II categories of power supply reliability) and other (III category) loads. This is determined by the need for improving the reliability of power supply to the critical loads and load-shedding the EPS without blackout. Currently, more than 45 % of residential consumers and 20 % of industrial ones included in the temporary blackout schedules are supplied with power via feeders with mixed load,

– Widespread implementing reclosers and/or additional switching devices to ensure the grid survivability under the various circuit and operating conditions (reconfiguring for optimal localization of faulty sections, ensuring reliable power supply to the maximum possible number of consumer electrical installations),

– Mass-scale implementing automated control systems for regular and emergency operation modes of grids – mini-grids, microgrids, and multi-microgrids,

– The use of small-sized phasor measurement units (PMUs) as sensors for relay protection and automated control systems, which allow calculating the required parameters for each connection and the entire grid based on the current and voltage synchronization vectors,

– The use of multifunctional digital devices with a remote on-line change of settings to ensure the RP and automation functions, depending on the circuit and operating conditions, without disconnecting and restarting them,

– Combining the RP, AE, and MA functions in multifunctional digital field devices, implementing improved mode parameter evaluating algorithms and automation ones adapted to DERs in grids,

– Mass-scale use of power converters at

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microgeneration facilities (up to 15 kW), implementing plug-and-play technology (free integration of new power market participants).

A typification of technical solutions for mini-grids and microgrids (structural solutions, arranging data transmission channels, principles of ensuring cybersecurity, etc.) is required to ensure the reliable EPS operation and reduce the cost of their implementation projects.

5 Development of technical requirements for DERs

The need to develop mandatory technical requirements for DERs is determined by the need for integrating them without creating problematic issues to ensure the reliable operation of distribution grids and power supply to consumers.

Technical requirements for DERs should include:

– Requirements for the resistance of DERs to changes in the current frequency and participation in automated frequency control,

– Requirements for resistance to long-term changes and short-term drops of voltage and participation in the control over voltage and var flows,

– Requirements for the power quality indicators at the point of common connection to the distribution grid,

– Requirements for a permissible fault-current contribution at the point of common connection to the distribution grid,

– Requirements for automation instruments used for the selection to the main mode with a balanced load to ensure reliable operation in this mode until synchronization with the EPS,

– Requirements for the GU DER maneuverability (start-up duration, control range, permissible load change rate),

– Requirements for participation in the restoration of the power system (mini-grid, microgrid) after eliminating the EPS accidents, including the black start,

– Requirements for equipping with RP and automation and power measuring and commercial metering devices,

– Requirements for equipping with data transmission and control action (command) receiving systems, equipment monitoring, remote control, automatic synchronization, etc.,

– Requirements for the availability of descriptions of mathematical GU models (including the automated control system algorithms) and data to calculate steady-state modes, transient processes, and SC currents,

– Requirements for the scope and results of tests to confirm the DER compliance with the above requirements.

The technical requirements for DER should be drawn up based on the package principle, considering the peculiarities of Russia's UES, GU, and the operating modes of distribution grids they are integrated.

It is advisable to determine the lower capacity limit of 1 kW for the microgeneration facilities, to which technical requirements will not be applied.

It is expedient to structure the technical requirements for DERs with capacity within 1 kW to 0.5-1 MW connected to 0.4 kV grids as follows:

– Technical requirements for microgeneration facilities with a capacity of 1 to 15 kW, regardless of the type (to be implemented in reversible converters),

– Technical requirements for photovoltaic power plants with a capacity of 15 kW to 0.5-1 MW,

– Technical requirements for wind power plants with a capacity of 15 kW to 0.5-1 MW,

– Technical requirements for thermal power plants with a capacity of 15 kW to 0.5-1 MW.

Technical requirements for DERs and their connection to 6-35 kV grids with a capacity of 0.5-1 to 5 MW and those with a capacity of 5 to 25 MW should be drawn up with a similar gradation for photovoltaic, wind, and thermal power plants [13].

Also, a list of new equipment (energy storage systems, devices with power converters, etc.), which has already been used in pilot projects or is planned to be used in the near future, should be drawn up, and the relevant technical requirements developed.

It is important to note that deviations in the power quality indicators limit the use of existing digital mode parameter measuring techniques in digital devices; therefore:

– It is expedient to synthesize the digital signal processing algorithms, which allow simultaneously evaluating several parameters of measured power quantities,

– To ensure the proper operation of RP and AE devices, the parameter evaluation speed should be increased, while maintaining sufficient accuracy, therefore, the frequency, voltage, and current values should be considered as random variables [14, 15],

– Statistical evaluation techniques are effective against the background of random changes in the mode parameters and the impact of distorting factors, which provide accurate results due to the use of special stochastic procedures.

Accurate measurement of the components of the complex voltage, frequency, and rate of their change is the basis for determining the types and scope of control actions of the AE devices, implementing algorithms in the RP, PMU, and power quality control devices, etc.

6 Development of the DER-based power distribution schemes

The DER-based power distribution schemes (PDS) should be developed in six successive stages, which differs from the current requirements for developing the power plant PDSs:

– Choosing the unit capacities and the GU types for DERs based on possible operating modes and load schedules,

– Developing a preliminary PDS to draw up additional technical requirements for GUs, in addition to the common ones, and choosing specific GU types to minimize the cost of implementing technical measures in the external and internal power grids,

– Requesting the GU technical specifications from the manufacturers to evaluate the operation algorithms, the parameters of configuring the RP and process protection devices, automation instruments, automatic speed and excitation controllers, and automatic GU control systems to identify the specifics of their operation in abnormal and emergency modes,

– Developing final DER PDS to determine the suitability of the chosen GU types for the power supply and consumption conditions and the distribution grid operating modes, considering the costs of commissioning new equipment and retrofitting the existing one, as well as RP, AE, MA, process protection, and automation devices,

– Coordinating the final DER PDS with the network arrangement and the operational dispatch control subject (if required),

– Drawing up terms of reference for the GU supply along with the substantiated technical requirements (basic and additional) for GUs, which are the result of the developing and coordinating PDS.

This approach to developing the DER PDS allows drawing up additional technical requirements for GUs to choose their type and further evaluate their suitability to function in the specific circuit and operating conditions and the grid operating modes [16-18].

Methodically, the calculation of power supply modes for the parallel operation of DERs and EPSs does not significantly differ from that for the island mode. However, the calculations for the DER-based grid have many features to be considered to obtain accurate results and make sound technical solutions [19, 20].

Conclusion

Under the EPS transformation conditions, the approaches to designing the distribution grids should be changed (building principles, automation, automated control of modes, etc.).

The technical requirements for the DER-based power generation units considering the possibility of their operation in the island mode and new equipment that has not been previously used in distribution grids should be developed.

The current technical requirements for power equipment, relay and emergency protection, and mode automation devices (measuring bodies, operation algorithms, configuration parameters) should be changed.

The approach to the development of power distribution schemes for the DERs proposed considering the peculiarities of modern GUs and loads allows ensuring the reliable DER operation as part of the EPS.

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