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SELF-HEALING OF ELECTRICITY SUPPLY IN INTELLIGENT LOCAL ELECTRIC POWER SYSTEM BASED ON RENEWABLE SOURCES OF ENERGY

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With the increase in the power grid capacities of renewable sources of energy (RSE) and the implementation of measures and means to compensate for the dependence of their generation on natural conditions, the role and importance of RSE in electric power systems (EPS) is changing. RSE are real opportunity to decentralize electricity generation and provide power supply systems with a reliable source of energy. It is shown that it is advisable to do this in the form of local electric power systems (LEPS), which operate in normal modes in parallel with the EPS as balancing groups, and in extreme conditions are able to operate in isolation in an autonomous mode. To ensure the reliability and quality of electricity supply to electricity consumers in to LEPS offered to integrate RSE and energy storage systems (ESS) in the form of separate microgrid (MG). To ensure technical and economic efficiency, MGs are combined into an intelligent control system based on SMART Grid principles. This allows for more rational use of MG resources, effective interaction with the distribution grid, and the use of EES as RSE reserve in the process of balancing the LEPS. The research offers a hierarchical structure of the intellectual system of LEPS as consisting of individual agents designed to respond to the variable current states of the LEPS and form collective actions to ensure reliable power supply to consumers. Autonomous agents make control decisions and form a multiagent system. LEPS with intelligent electric grids structured in this way can avoid losing renewable sources of energy during centralized power supply constraints and fully use their advantages together with energy storage systems to ensure reliable power supply to consumers. Ref. 17. Fig.4.

Key words: *local electric power systems, autonomous mode, renewable sources of energy, intelligent control system.*

САМОВІДНОВЛЕННЯ ЕЛЕКТРОПОСТАЧАННЯ В ІНТЕЛЕКТУАЛЬНІЙ ЛОКАЛЬНІЙ ЕЛЕКТРОЕНЕРГЕТИЧНІЙ СИСТЕМІ, СФОРМОВАНІЙ НА ОСНОВІ ВІДНОВЛЮВАНИХ ДЖЕРЕЛ ЕНЕРГІЇ

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Зі збільшенням в електричних мережах енергосистем потужності відновлюваних джерел енергії (ВДЕ) та впровадженням способів і засобів компенсації залежності їх генерування від природних умов змінюється їх роль і значення в електроенергетичних системах (ЕЕС). ВДЕ є реальною *можливістю децентралізувати генерування електроенергії й забезпечити системи електропостачання надійним джерелом енергії. Показано, що це доцільно робити у формі локальних електроенергетичних систем (ЛЕС), які працюють в нормальних режимах паралельно з ЕЕС як балансувальні групи, а в екстремальних випадках здатні працювати ізольовано в автономному режимі. Для забезпечення надійності та якості електропостачання споживачів електроенергії в ЛЕС пропонується інтегрувати ВДЕ та системи накопичення і зберігання енергії (СЗЕ) у вигляді окремих microgrid (MG). Для забезпечення техніко-економічної ефективності MG об'єднуються в інтелектуальну систему керування на принципах SMART Grid. Це дозволяє раціональніше використовувати ресурси MG, ефективно взаємодіяти з розподільчою мережею і задіяти можливості СЗЕ як резерву ВДЕ в процесі балансування режиму ЛЕС. У роботі запропоновано ієрархічну структуру інтелектуальної системи ЛЕС як таку, що складається з окремих агентів, призначених реагувати на змінні поточні стани ЛЕС і формувати колективні дії для забезпечення надійного електропостачання споживачів. Автономні агенти приймають рішення з керування і складають мультиагентну систему. Структуровані в такий спосіб ЛЕС з інтелектуальними електричними мережами можуть під час обмеження централізованого електрозабезпечення не втрачати ВДЕ, а повною мірою використовувати їх переваги разом з системами накопичення і зберігання енергії для надійного електропостачання споживачів. Бібл. 17. Рис. 4.*

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Ключові слова: *локальні електроенергетичні системи, автономний режим, відновлювані дже-рела енергії, інтелектуальна система керування.*

List of Abbreviations and Symbols

DSO – distribution system operator

EPS – electric power system

ESS – energy storage system

ECD – electrochemical storage device

LEPS – local electric power systems

PVPP – photovoltaic power plants

RSE – renewable sources of energy

WPP – wind power plant

Introduction and formulation of the problem. With the development of renewable sources of energy (RSE) in the power grids of electric power systems (EPS) and decentralization of generation, it has become possible, and to some extent necessary, to organize local electric power systems (LEPS) based on RSE. LEPS can operate in parallel with the EPS as a separate balancing group, consuming or generating electricity into the system. Under certain conditions, based on economic interests or due to an extreme condition in the EPS, LEPS can operate autonomously as an isolated intelligent system [1-3]. At the level of the power generation and distribution system, a LEPS is considered as a set of microgrids, which are a group of interconnected loads and distributed generation facilities, including mainly renewable sources of energy [4, 5].

Similar problems and tasks arise in the local electric power system as in the EPS: mode balancing, frequency and voltage regulation, reduction of power losses and improvement of power quality, improvement of power supply reliability by reducing SAIFI and SAIDI. Modern LEPS are formed on the basis of renewable sources, the largest part of which is photovoltaic and wind power plants (PVPP and WPP). Since the generation of electricity by PVPP and WPPs depends on weather conditions, power storage systems are forced to reduce the unbalance that can be caused by their variable generation. In one way or another, all of these factors affect the modes of operation of LEPS and the quality of electricity supply to consumers. The increase in electricity generated by RES in the EPS causes more frequent and significant power fluctuations in the system and increases its operational risks. Operational dispatching has little chance of coping with generation instability. Often, the operator's actions, depending on the state of the power system - surplus or deficit of electricity - are reduced to limiting the generation of electricity from RES or reducing consumer load. This problem can be solved in the interests of both the electricity producer and the consumer if the LEPS is equipped with direct and reverse power conversion technologies. Surplus electricity after balancing can, for example, be stored in the form of energy from electrochemical storage devices (ECDs) or hydrogen produced as a result of electrolysis. The reverse process of returning electricity to the LEPS is carried out as needed, usually in the morning and evening peak load conditions or during emergencies. It is not possible for an electricity distribution system operator (DSO) to effectively manage such a complex process of electricity generation, transmission, distribution and conversion in order to balance the system mode reliably and without losses. Today, technologies developed on the principles of SMART Grid successfully cope with this problem [6-8]. The concept of an intelligent system provides greater opportunities for monitoring and controlling power system components, as well as increasing the reliability, quality and efficiency of electricity supply to consumers. A key characteristic of an intelligent system is self-healing, which is defined as the ability of electricity distribution systems to automatically recover from failures [9]. Self-healing is an important feature of smart distribution systems that minimizes the impact of extreme events and automatically restores load during such incidents [10]. The self-healing system uses various modern methods to ensure stable, reliable and safe power supply at consumer facilities [11, 12]. Nevertheless, the implementation of self-healing control methods and their corresponding efficient operations remains a challenge for local electric power systems.

The goal of the article is to justify the conditions for self-healing of power supply in a local electric power system with renewable sources of energy and an intelligent control system.

Local electric power system with microgrid as an intelligent system. To study the problem of self-healing of power supply, consider the LEPS as a balancing group, which is shown in Fig. 1. A LEPS is considered as a part of the EPS with the possibility of centralized power supply, as well as with its own energy sources. A LEPS is formed on the basis of renewable sources of energy (PVPP, WPP) and is equipped with a system of power conversion and storage devices (ESS) to maintain the balance of electricity in it. The balance of electricity in the LEPS shown in Fig. 1, is recorded in the balancing group:

$$\begin{aligned} &\pm P_{EPS}(t) + P_{RSE}(t) \pm P_{ESS}(t) - P_{con}(t) - \\ &- P_{ac}(t) - \Delta P(t) = 0 \end{aligned}, \quad (1)$$

where $P_{EPS}(t)$ – power from EPS; $P_{RSE}(t)$ – power of RSE; $\pm P_{ESS}(t)$ – power of ESS; $P_{con}(t)$ – power of electricity consumers operating on their schedule; $P_{ac}(t)$ – capacity of active consumers operating on an adjusted schedule; $\Delta P(t)$ – technological costs in electric grid of LEPS.

The balancing of the LEPS modes, including the LEPS as a part of it, is carried out according to hourly load and generation schedules, which are forecasted for the day ahead and can be adjusted during the current day [13]. If an hour is taken as a time interval, then the following electricity values are typical for a LEPS:

– $W_L = \sum_{i=1}^{24} \Delta t \, P_{L_i}(t)$ – electricity of the total load, including losses;

– $W_{RSE} = \sum_{j=t_n}^{t_\kappa} \Delta t \, P_{RSE_j}(t)$ – electricity generated by RSE, where t_{start}, t_{end} are the start and end time of generation;

– $W_{ESS} = \sum_{j=t_1}^{t_2} \Delta t \, P_{RSE_j}(t) - \sum_{j=t_1}^{t_2} \Delta t \, P_{L_i}(t)$ – surplus electricity in the LEPS, which can be transferred to the energy storage system or to the EPS;

– $W_{unbal} = W_L - W_{RSE} + \Delta W$ – electricity that needs to be taken for the balance in the LEPS from ESS, EPS or energy sources with available maneuverable power.

If a LEPS consists of electricity consumers with different characteristics (different reliability categories, power quality requirements, etc.), as well as electricity sources that differ in their operating principle and technical characteristics, it is logical to represent them as multi-microgrid [5]. For such LEPS, various control schemes are possible: centralized, distributed, hierarchical and MAS-based management scheme [6]. For a LEPS that implements an intelligent self-healing power supply system, a multi-component hierarchical MAS control system is proposed (see Fig. 2) [8].

In Fig. 2, at the upper level, the local agent LEPS A is an element of the lower level of the electricity distribution system operator (DSO). When operating in parallel with the EPS at this level, the LEPS A performs the functions of a balancing group within the power system, coordinating its actions with the DSO. The main task is to forecast the generation and consumption of electricity in the LEPS and to exchange electricity with the EPS. For this purpose, a database is formed through requests for information from the microgrid middle agents MG A and MG A_i. MGA to determine the technical resource and the degree of readiness of manoeuvrable power facilities and MG Ai as agents that unite separate groups of RSE, ESS and electricity consumers.

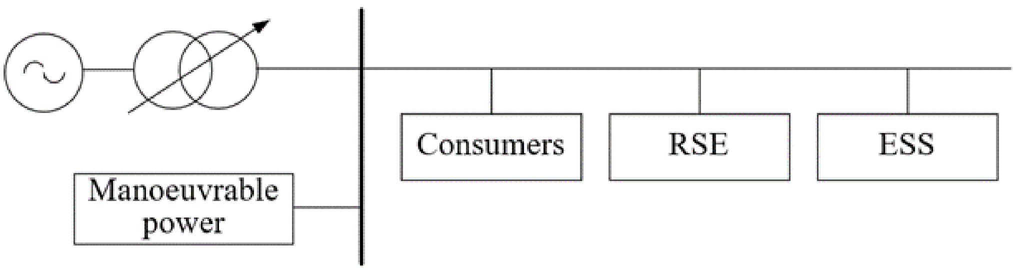

Fig. 1. Local electric power system as part of the EPS

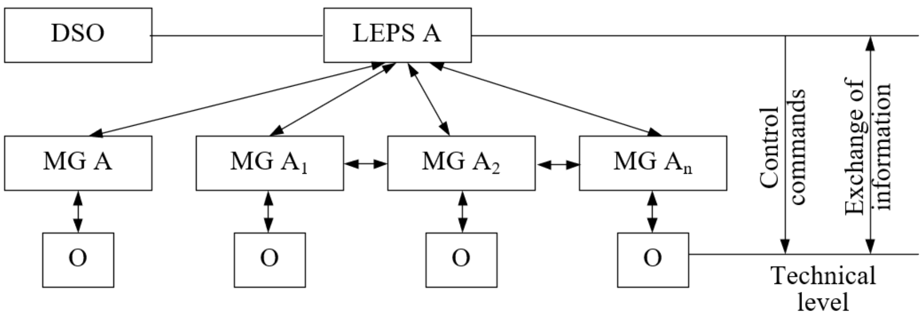

Fig. 2. The hierarchical structure of the intelligent system of LEPS

The MGA agent is the agent through which, if necessary, the services of the EPS are implemented to balance the LEPS. The MGA, through the LESA, coordinates the energy storage systems deployed in the microgrid of the LEPS, and assesses the availability of the managed distributed energy sources for intraday generation correction at the command of the LESA. It manages the common EES by maintaining frequency and also manages reactive power sources by maintaining voltage. MGA_i agents are microgrid agents that are responsible for communicating with their agents at the technical level: PVPP, active consumer, inactive consumer, local ESS. It optimises technical and economic parameters based on data from local agents and downloads the result of optimisation of the respective microgrid zone (power surplus/deficit, energy storage state, active consumer capabilities). Each agent is responsible for communication to download relevant data and receive operating commands and interact with each other. With a direct connection to the equipment, it functions as a distributed control system where each agent performs its functions independently but can interact with other agents for coordination.

When LEPS is separated from the EPS, the tasks and essence of the functions to be performed automatically by the intelligent system change. The LESA is responsible for internal power and electricity balancing and maintaining the technical and economic indicators of the power supply system within acceptable values. This primarily concerns the maintenance of the frequency and voltage on the consumer buses in the LEPS. This is done through the collective actions of middle and technical level agents by issuing appropriate operating commands to these agents. Optimal control of active consumers within the limits of power consumption W_{ESS} [8] is carried out, as well as limiting, if necessary, the power of inactive consumers.

There are two possible options for setting LEPS to isolated operation: forced, when the power grid loses voltage for some reason, or in normal mode, when the LEPS is disconnected at the initiative of the DSO or LEPS A. In these cases, commands are sent to the MGA according to the intelligent system software and the LEPS is switched to offline mode. When connecting the LEPS to the EPS, all procedures related to the synchronisation of the two power grids are performed before sending a command to the circuit breaker. These tasks are a function of the intelligent system, which is commonly referred to as self-healing of the power supply [14].

Self-healing of power supply in LEPS. Self-healing is the ability of power systems to automatically recover from failures [15]. Self-healing is potentially the most important function of smart electricity distribution systems, which helps to minimise the impact of extreme conditions and automatically reconnect disturbed loads. As an element of the Smart Grid, self-healing is based on the functions of two-way communications in the grid, distance monitoring and self-diagnosis of equipment, standards for preventing the development of systemic failures, controlling power flows and voltage, etc. [16]. The concept of an intelligent system provides more opportunities for managing and controlling power system components, as well as increasing the reliability, resilience and efficiency of the power system. Self-healing is an important feature of smart distribution systems that minimises the impact of extreme events and automatically restores power supply during such incidents [17].

The principle of operation of the self-healing system during forced LEPS failures includes detection, isolation and restoration of power supply. The power supply is restored automatically during emergencies through effective monitoring and decision-making without the intervention of operational personnel, which significantly reduces SAIFI. Depending on the balance of power generation and consumption, LEPS can be fully or partially restored to the power supply.

During the operation of a LEPS, two typical cases are possible that require the use of the self-healing function of an intelligent system: LEPS loses connection with the EPS and is forced to switch to autonomous mode; emergencies occur within the LEPS it self, which are self-limited and, depending on their severity, can lead to disconnection from the EPS grid or not.

Fig. 3 shows the first case, when, for example, an extreme situation occurs in the EPS and the voltage source for the LEPS is lost. In this case, a transient mode is installed in the LEPS, in which consumers with autonomous power supply and power sources of the ESS type remain in operation, which are permanently connected to the power grid and are in or automatically switched from the 'charge' to the 'discharge' mode. Actions to self-healing power supply begin with an assessment of the real unbalance of electricity $P_{unbal}(t)$ in the LEPS:

$$\begin{gathered}P_{RSE}(t)+P_{ESS}(t)+P_{MGA}(t)-P_{con}(t)-\\-P_{ac}(t)-\Delta P(t)=P_{unbal}(t)\end{gathered}, \quad (2)$$

where $P_{RSE}(t)$ is the power that, according to the adjusted forecasted generation schedule, all RES in the RSE can generate, starting from the time of disconnection from the EPS t; $P_{ESS}(t)$ is the total capacity of the ESS of all microgrid MGA$_i$ at time t; $P_{MGA}(t)$ - is the power that the local agent of the LEPS A can use from the manoeuvrable power resources of the MGA to maintain the frequency in the isolated LEPS for time t and later; $P_{con}(t), P_{ac}(t), \Delta P(t)$ – electricity consumption in LEPS.

Depending on the value of the unbalance $P_{unbal}(t)$, the software tools of the intelligent system generate a schedule of electricity consumption in the LEPS. First, consumers are selected that must operate according to their normal load schedules for the reliability of power supply. The remaining consumers are divided into two groups: consumers that may be temporarily disconnected during an emergency; consumers that allow temporary interruptions in power supply and, under certain conditions, may be used to maintain the frequency in the LEPS (tertiary regulation).

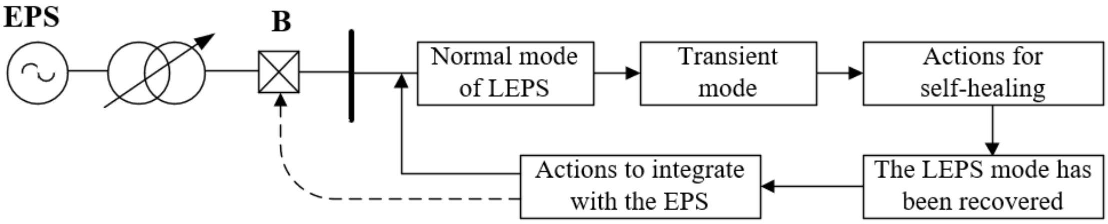

Fig. 3. Self-healing of power supply in LEPS in case of loss of connection with EPS

Primary and secondary frequency regulation is carried out by sources from RSE and centralised ESS. ESS in individual microgrids are advisable to use to cover their own load. Active consumers are also used to balance the LEPS mode. In this case, the power balance in the recovered LEPS mode is as follows:

$$\begin{gathered}P_{RSE}(t)+P_{ESS}(t)+P_{f}(t)-P_{con}^{'}(t)-P_{conf}(t)-\\-P_{ac}(t)-\Delta P(t)\approx 0\end{gathered}, \quad (3)$$

where $P_f(t)$ is power allocated from regulated RSE and ESS to regulate power and frequency in LEPS; $P_{con}^{'}(t)$ is power of electricity consumers who continue to operate according to their normal load schedules; $P_{con\,f}(t)$ is power of electricity consumers that may be at risk of interruptions in power supply and can be used to maintain the frequency in LEPS.

When the voltage is recovered from the EPS, the LEPS is connected to the system with the permission of the DSO. To do this, the necessary actions are taken, which mainly consist of levelling the voltage on the LEPS buses, and the LEPS is synchronised with the EPS. Normal operation is recovered for consumers and power generation sources.

In Fig. 4 shows another case of self-recovery of power supply, when emergencies occur directly in the LEPS. Two scenarios are possible: LEPS is connected to the EPS and the malfunction in it did not result in the operation of relay protection in the EPS, the LEPS remained in parallel with the EPS; the emergency led to disconnection from the EPS. In the latter case, the algorithm of actions is similar to the case (see Fig. 3), when the power supply in LEPS is recovered as in the case of loss of connection with the EPS. The difference is that first, the relay protection and automation systems localise the damaged part of the power grid. The transient mode of LEPS is installed.

If the connection to LEPS is maintained, the first stage of the self-healing operations should be fault detection in order to avoid the adverse impact of abnormal events as soon as possible and to reduce losses to electricity consumers. The next stage of the self-healing process after fault detection is fault isolation. The fault is isolated by switching off the circuit breakers and disconnecting the damaged section. The isolation operation identifies the root cause of the fault and its location. By reconfiguring the power grid, we minimise power supply disruptions to consumers. If there are power sources in the isolated grid segment, their capacity is compensated either by reserve power LEPS or by paid services of the EPS. In the recovered mode, the following power balance is installed:

$$\begin{gathered}P_{EPS}(t)+P_{RSE}(t)+P_{ESS}(t)-P_{con}(t)-\\-P_{ac}(t)-\Delta P(t)\approx 0\end{gathered}. \quad (4)$$

In the recovered mode, the load of consumers may remain unchanged or decrease depending on the unbalance $P_{unbal}(t)$ in LEPS. The load schedule of active consumers is adjusted accordingly.

All actions for the self-healing of power supply are performed in the intellectual system of LEPS. Algorithms of actions of the function are achieved by control actions to change the configuration of the power grid by optimal switching. The power supply system recovering strategy is based on graph theory. The grid is reconfigured to minimise the number of switching operations. To reduce the number of switching operations, the power supply to loads and generation of electricity sources is restored structurally through microgrids. After the faults are fixed, actions are taken to recovery generation and power consumption of the localised part of the LEPS and normal operation is installed.

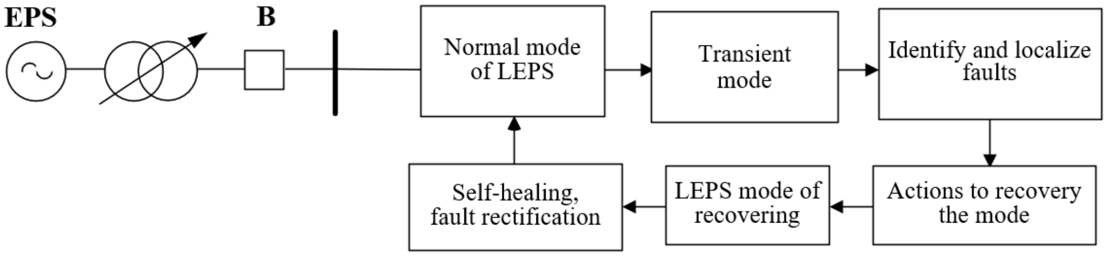

Fig. 4. Self-healing of power supply in LEPS due to emergency situations in it

Conclusions

With the development of renewable sources of energy and the implementation of means and measures that turn RSE into guaranteed sources of electricity, it has become possible to decentralize electricity generation and supply to power supply systems. It is possible and expedient to do this in the form of local electric power systems that can operate in parallel with the EPS as a separate balancing group or, if necessary, in isolation in an autonomous mode.

To improve the energy efficiency of LEPS, it is advisable to control its modes in the form of an intelligent system. An intelligent system of LEPS is built as a hierarchical structure that realizes the control of individual microgrid. As aggregated microgrids, these have own energy sources, energy storage systems, passive and active electricity consumers, and local automation. The task of the LEPS intelligent system is to ensure its operation in parallel with the EPS as a balancing group and in isolation in an autonomous mode. In autonomous mode, the system is controlled in cases when the LEPS has lost connection with the EPS and when emergency conditions arise in the LEPS directly. In all cases, the intelligent system ensures self-healing of power generation and reliable power supply to consumers.

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