DOI: https://doi.org/10.15407/techned2026.04.051

DIRECTIONS FOR DEVELOPMENT OF HIGH-POWER MICROGRIDS FOR INDUSTRIAL ENTERPRISES OF UKRAINE

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Research has been conducted into the directions of development of high-power microgrids capable of ensuring the uninterrupted operation of critical electrotechnological equipment at industrial enterprises of Ukraine under unstable external power supply conditions. Improvements to such microgrids are substantiated based on the use of autonomous distributed energy sources and modern technologies for accumulation, storage and conversion of electrical energy parameters, and on the integration of artificial intelligence and energy management methods. The key role of high-power microgrids in ensuring guaranteed power supply to critical energy consumers of industrial enterprises during prolonged outages and unstable external supply conditions has been identified. It is substantiated that the integration of high-power microgrids, modern "smart" mechanism technologies and hybrid energy systems at industrial enterprises increase the energy efficiency of all electrical, technological and organizational processes and their resilience to prolonged outages and external power supply instabilities. The introduction of high-power microgrids at industrial enterprises in Ukraine increases the energy efficiency of all electrotechnologies for the production of critically important products and facilitates the achievement of sustainable development goals. References 19, figure 1.

Key words: external macrogrid, industrial enterprise, critical energy consumers, power supply instability, electrotechnology, power quality, high-power microgrid, autonomous energy sources, energy storage devices, uninterruptible power supply, energy efficiency.

Introduction. Intense military operations on the territory of Ukraine cause significant instability in power supply from external centralised grids, affecting both populated areas and industrial enterprises (at any moment the power supply may suddenly disappear or substantially change its basic parameters). However, ensuring the high quality and economic viability of manufacturing many types of high-technology products of an electrical-energy and special purpose requires continuous high-quality power supply to critically important energy consumers for periods of several days or even weeks. At present, providing such stable power supply in Ukraine from external power supply systems is simply impossible.

At the same time, in our country, local power systems with distributed generation are being intensively developed, created and operated. These systems have their own autonomous energy sources which, during outages of the external centralised macrogrid, can provide autonomous power supply to various energy consumers of modest capacity (typically units to tens of kilowatts) [1–3]. However, such microgrids are unable to provide prolonged high-quality power supply to critically important energy consumers with capacity in the hundreds to thousands of kilowatts.

The purpose of this work is scientific and practical research aimed at determining the directions for development and practical implementation of high-power microgrids to ensure guaranteed high-quality power supply to critical energy consumers of industrial enterprises of Ukraine that are currently manufacturing critically important electrical-energy and technological products.

The key distinction of the high-power microgrids under study from known low-power microgrids is continuous guaranteed power supply to all critical energy consumers of an industrial enterprise for realising continuous high-quality electrical-energy operating modes, which are crucial for the manufacture of critically

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important electrotechnological products regardless of instabilities in external power supply conditions or even prolonged outages, as in [4].

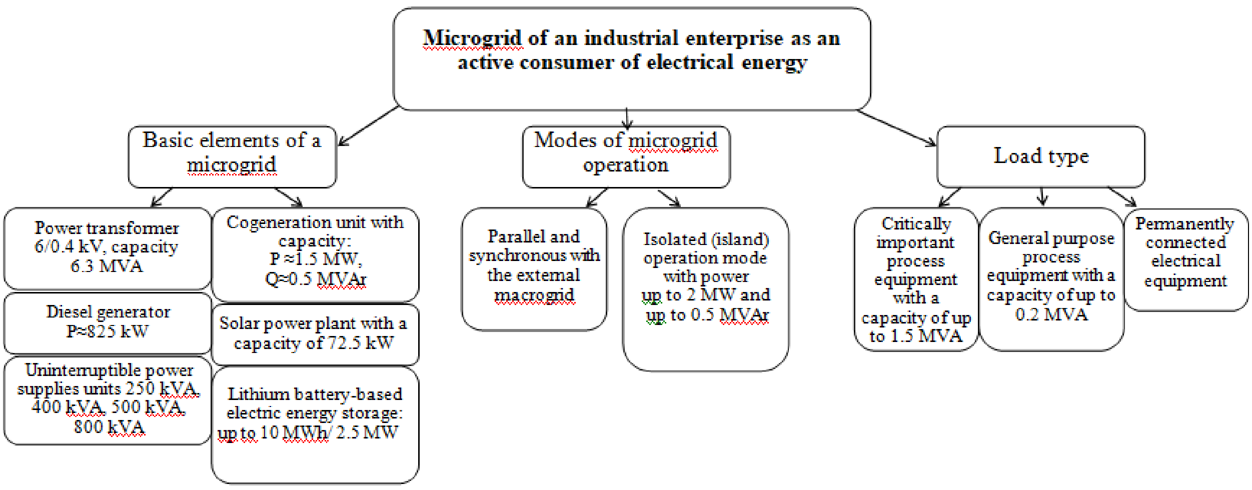
According to IEEE Standard 1547.4, a distributed generation power system is treated as a high-power microgrid that has its own autonomous energy sources and energy consumers (electrical loads). It is specially designed as a local power system capable of operating effectively in the so-called "island" mode [1–4], and can therefore be disconnected from the external macrogrid.

A high-power microgrid is a local power system that can utilise energy from autonomous power systems such as a gas cogeneration unit, a diesel generator and a solar power plant. To ensure guaranteed power supply to critical energy consumers of industrial enterprises and the high power quality required by them during prolonged outages and unstable operating modes of the external power supply system, the microgrid employs modern high-energy-capacity electrical energy storage devices and electronic equipment capable of providing fast energy resource management and power supply mode control to industrial energy consumers. High power quality and stability of supply to critical consumers under any energy disturbances in the external macrosystem is achieved both during synchronous operation of the microgrid with the macrogrid and during its prolonged autonomous ("island") operation, as well as during implementation of so-called fast "seamless" transitions between these modes.

However, having a limited maximum capacity, the microgrid is primarily directed at ensuring the required high-quality power supply to its critical energy consumers under any electrical and electrodynamic disturbances in the external macrogrid. Of course, if the microgrid provides guaranteed power supply to critical consumers of various capacities, the most powerful consumers are supplied, wherever possible, with the least expensive electrical energy from the solar power plant [4, 5], or at minimum electricity tariffs from the external macrogrid when it is operational. Nevertheless, ensuring guaranteed power supply to all critical energy consumers of the high-power microgrid is always the most important and overriding priority (compared to electricity cost, convenience and all other parameters).

Reliable and energy-efficient operation of a microgrid depends on the quality of interaction among all components of the control, energy supply and mode stabilization systems, and so on, which presents a separate challenge for effective power supply [6–8]. Notwithstanding this, high-power microgrids of industrial enterprises are important elements of industrial energy systems and "smart enterprises" [9–13].

Structure and main components of high-power microgrids. The authors of this paper participated in the development, creation and long-term (more than one year) operation of a microgrid with a capacity exceeding 2 MW, comprising a gas cogeneration unit with active power of 1.5 MW and reactive power of 0.5 MVAr, a diesel generator with capacity up to 825 kW, and a solar power plant with capacity up to 72.5 kW. The structural diagram of the high-power microgrid is presented in Figure.



The key components of high-power microgrids similar to that shown in Figure are: autonomous distributed energy sources; modern fast-acting systems for conversion of electrical energy parameters, accumulation, storage and generation; and control systems for the processes of power supply to critical consumers both in "synchronous" modes with the external macrogrid and in "island" modes with "seamless" (practically instantaneous) transitions between such modes [3].

The ability of a high-power microgrid to operate both synchronously with the macrogrid and independently of it is the key characteristic of the resilience of the microgrid operating modes to energy disturbances in the external macrogrid [14, 15]. This dual functional capability of high-power microgrids is especially important for power supply in limited territories with specific energy requirements in regions where connection to the central macrogrid is a complex task.

To improve fast electrodynamic processes in high-power microgrids, it is advisable to use high-energy-capacity storage batteries based on modern electrochemical accumulators and technologies for optimising their dynamic modes under industrial conditions [16–18].

The main power supply sources in the high-power microgrid presented in Figure were a cogeneration unit with capacity $P_1 \leq 1.5$ MW, a diesel generator with capacity $P_2 \leq 825$ kW and a solar power plant with capacity $P_3 \leq 72.5$ kW. Their total active power amounts to $P_\Sigma \geq 2.3$ MW.

The cogeneration unit can produce the greatest amount of electrical energy, and its cost is lower than that generated by the diesel generator. Moreover, when thermal energy produced by the cogeneration unit was also utilised at low external temperatures – and the quantity of thermal energy exceeded the electrical energy generated – the overall energy efficiency of the cogeneration unit approached 90%, making it the key autonomous energy generator in the given microgrid.

The most economical energy is naturally that from the solar power plant; however, its maximum capacity of 72.5 kW is small and highly variable, so this energy was used for diagnostics of electrical characteristics of low-capacity instruments and for energy storage.

All loads in the high-power microgrid in Figure are conventionally divided into three categories: ***critically important, priority and controlled non-priority load.***

1. *The critically important load* comprises 4 electrotechnological production lines for critically important electrical-energy products and all electric servers, electrical safety systems and systems monitoring the existing electrical-energy and technological processes.

This load must have uninterrupted, guaranteed and high-quality power supply under any conditions of disconnection from or mode changes of the external macrogrid. When emergency modes arise therein, all critical loads must be instantaneously (in less than 1 ms) disconnected from it and "seamlessly" connected (using four uninterruptible power supply units: UPS 800 kW, UPS 500 kW, UPS 400 kW and UPS 250 kW) to the microgrid with total capacity $P_\Sigma \geq 2.3$ MW shown in Figure. As a result of these "seamless" switchings, all critically important loads must receive power from the gas cogeneration unit and the diesel generator. Additional final correction of all fast "seamless" transient modes is provided by the 10 MWh energy storage device indicated in Figure, which employs modern high-energy lithium iron phosphate accumulators capable of delivering active power up to 2.5 MW for at least 4 hours.

To ensure the required high quality and competitive economic viability of manufacturing especially important energy products, the specified high-power microgrid must provide continuous high-quality power supply to some high-capacity critically important consumers for several days or even weeks. Therefore, the requirements for realising the necessary prolonged, uninterrupted and high-quality electrical-energy operating modes are key considerations in the development, creation and operation of high-power microgrids for power supply to *critically important electrotechnological loads.*

2. *Priority load* comprises the "non-critical technological general-purpose electrical equipment" and other electrical consumers shown in Figure, whose connection schedules may be varied, but without disrupting the operating modes of critically important loads. Priority loads may also include electrotechnological installations and other electrical equipment whose operation can be planned with extended intervals and postponements of their power supply schedules, provided these do not affect the operating quality of critically important loads.

3. *Non-priority controlled load.* The schedules and capacity of power supply to non-priority controlled loads may be altered and rescheduled both during work planning and during execution. The only overriding constraint is the impermissibility of disrupting the continuous guaranteed power supply to all critical energy consumers of the industrial enterprise for realising prolonged uninterrupted and high-quality electrical-energy operating modes, which are crucial for the manufacture of critically important electrotechnological products regardless of instabilities in, or outages of, the external power supply to the industrial enterprise.

High-power microgrids for industrial enterprises differ from conventional low-power general-purpose microgrids in their greater scale, the need to implement more complex guaranteed power supply operating modes for all critical energy consumers, specialised requirements for the optimisation and integration of energy resources for their realisation, and heightened requirements for energy efficiency and the realisation of prolonged continuous critical electrotechnological production modes [15, 17].

Advantages of creating high-power microgrids for industrial enterprises of Ukraine.

During the current wartime, high-power microgrids represent practically the only energy-efficient electrical engineering solution for guaranteed, high-quality power supply to critically important electrotechnological equipment of industrial enterprises of Ukraine, despite the instability of operating modes and unpredictable prolonged outages of centralised power supply. The construction and use of a high-power microgrid by an industrial enterprise makes it possible to ensure the independence of all critically important electrotechnological processes and the general activities of the enterprise from the quality of electrical energy in the external power system and from the stability of its supply to the enterprise's electrical network.

The use of high-quality power supply from a proprietary high-power microgrid ensures guaranteed accumulation of electrical energy (i.e. storage for future consumption), stabilisation of peak loads at the enterprise, and also, during certain time intervals, generation and supply of electrical energy to the external grid for third-party consumers.

Implementation of the above-mentioned energy strategy provides the possibility for an industrial enterprise to transition from the status of an "electricity consumer" to that of an "active electricity consumer". By virtue of its own generating and storage equipment, the enterprise can not only meet its own electricity needs but also supply to the city grid up to 50% of its total annual electricity consumption to power third-party consumers during periods when the electricity price is at its highest. This enables the industrial enterprise to generate additional revenue that can be used for further development of the enterprise.

The key development vector for high-power microgrids in the near term should be considered to be the development and use of: (1) megawatt-scale electrical energy storage devices; (2) fast-acting storage devices for peak load coverage; (3) electrotechnological equipment capable of reliable operation under conditions of limited capacity; and (4) integration of artificial intelligence methods for effective energy management in the high-power microgrid.

The following key advantages of creating and using high-power microgrids at industrial enterprises of Ukraine can be identified [15, 19]:

– Substantial improvement of the reliability and resilience of power supply to critical energy consumers regardless of instabilities in the external power supply modes;

This is the primary advantage of creating and using high-power microgrids by industrial enterprises of Ukraine during the current wartime, since such microgrids are capable of providing guaranteed high-quality power supply to critical energy consumers of enterprises manufacturing domestic knowledge-intensive and important electrical-energy and technological products with high added value;

– Ensuring autonomous operation of high-power microgrids, which can be disconnected from the main macrogrid in the event of prolonged disruptions and unstable modes therein, and can guarantee the continuation of critical technological and industrial processes and even vital operations and procedures in hospitals and medical facilities;

– Prevention of stoppages and prolonged downtime of technological equipment that must operate in prolonged continuous modes, which are difficult to realise under current conditions of instability in external power supply;

– Enhancement of overall electrical-energy security, which is vital for the effective functioning of both industrial and information infrastructure;

– Reduction of overall industrial enterprise costs through implementation of various electrotechnological energy storage modes during periods of minimum electricity production costs, and even through selling to the city macrogrid electricity for which the price is at its maximum;

– Cost optimisation both when using electricity for manufacturing critically important industrial products and when accumulating electricity and subsequently selling it to third-party consumers during periods when its price is highest;

– Ensuring effective integration of renewable energy sources (RES) into industrial processes, which promotes the integration of renewable energy and reduces the environmental impact of industrial enterprises, directing their principal activities towards achieving sustainable development goals.

Conclusions. 1. At present, *the creation and use of high-power microgrids represents practically the only energy-efficient electrical engineering solution* capable of ensuring continuous guaranteed power supply to critical energy consumers of industrial enterprises of Ukraine for realising prolonged continuous high-quality electrical-energy operating modes, which are crucial for manufacturing critically important electrotechnological products regardless of instability in external supply modes or prolonged outages.

2. The *key distinction* of the high-power microgrids under study for industrial enterprises of Ukraine from known low-power microgrids is continuous guaranteed power supply to all critical energy consumers of an industrial enterprise, which are crucial for the manufacture of critically important products.

3. Notwithstanding the existing scientific, electrical engineering and technological barriers, high-power microgrids will inevitably become an integral part of future electrical energy systems capable of providing continuous guaranteed power supply to critical energy consumers of industrial enterprises of Ukraine regardless of instabilities in external supply modes or prolonged outages. They will play a key role in achieving resilience and energy efficiency.

4. Analysis of the main advantages and challenges enables industrial enterprises of Ukraine to fully realise the potential of this new technology — the construction of high-power microgrids — for enhancing the reliability of continuous energy supply and the manufacture of critically important electrotechnological products regardless of instability in external supply modes or prolonged outages. High-power microgrids increase energy independence by giving industrial enterprises the ability to produce and control their own electrical energy, and reduce dependence on external electricity service providers, thereby protecting industrial enterprises from energy price fluctuations and interruptions in electricity supply.

5. The key development vector for high-power microgrids in the near term should be considered to be the development and use of: (1) megawatt-scale electrical energy storage devices; (2) fast-acting storage devices for peak load coverage; (3) electrotechnological equipment capable of reliable operation under conditions of limited capacity; and (4) integration of artificial intelligence methods for effective energy management in the high-power microgrid.

The research was carried out under the R&D project "Ensuring the efficiency of the functioning and development of distributed energy in Ukraine using microgrid technologies" (Research code "Mode 3", State Registration No. 0125U000609).

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НАПРЯМИ РОЗВИТКУ ПОТУЖНИХ МІКРОМЕРЕЖ ДЛЯ ПРОМИСЛОВИХ ПІДПРИЄМСТВ УКРАЇНИ

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Проведено дослідження напрямів розвитку потужних мікромереж, здатних забезпечити безперебійну роботу критичного електротехнологічного обладнання промислових підприємств України за нестабільних режимах зовнішнього електропостачання. Обґрунтовано удосконалення таких мікромереж на основі використання автономних розподілених джерел електроенергії та сучасних технологій накопичення, збереження і перетворення параметрів електроенергії та інтеграції методів ***штучного інтелекту*** *й енергоменеджменту. Визначено ключову роль використання потужних мікромереж задля забезпечення гарантованого електроживлення критичних енергоспоживачів промислових підприємств під час тривалих відключеннях і нестабільних режимах зовнішнього електропостачання. Обґрунтовано, що інтеграція на промислових підприємствах потужних мікромереж, сучасних технологій "розумних" механізмів і гібридних енергосистем підвищує енергоефективність всіх електроенергетичних, технологічних і організаційних процесів та їхню стійкість до тривалих відключень і нестабільностей зовнішнього електропостачання. Впровадження потужних мікромереж на промислових підприємствах України підвищує енергоефективність всіх електротехнологій зі створення критично важливої продукції та спрощує досягнення цілей сталого розвитку*. Бібл. 19, рис. 1.

Ключові слова*:* зовнішня макромережа, промислове підприємство, критичні енергоспоживачі, нестабільність електроживлення, електротехнологія, якість електроенергії, потужна мікромережа, автономні джерела електроенергії, накопичувачі енергії, безперебійність, енергоефективність.

Received 01.06.2026
Accepted 22.06.2026