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Microgrids – Current Developments and Challenges

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Abstract – In recent decades, the concept of microgrids has become a key component in the modernization of electrical systems, particularly in developed countries. Microgrids enable the integration of distributed energy resources, such as renewable energy sources (solar panels, wind turbines), and energy storage systems, into existing distribution networks. This approach provides greater efficiency, flexibility, and resilience to energy disruptions, while also reducing harmful emissions. However, while microgrids offer numerous advantages, they also pose a range of challenges and issues related to the technical, regulatory, and economic aspects of their implementation. Technical challenges include optimizing the real-time operation of the microgrid, managing energy consumption and production, and ensuring network stability in the face of variability in renewable energy sources. The regulatory framework and energy market models must also evolve to support the integration of microgrids and ensure a fair market environment. This paper explores the key challenges associated with the development of microgrids, as well as the open questions that still await answers to enable their widespread deployment and optimal functioning.

Index Terms – Distributed energy resources (DER), Microgrids, Control strategies within microgrids, DER models

I INTRODUCTION

Due to the global population growth and the improved quality of life, the demand for electrical energy has been constantly increasing. As a result of the increased demand for electricity on the worldwide scale, the issue of balancing the energy produced by traditional large-scale power plants arises. The production capacities of traditional power plants are fully utilized and cannot be physically expanded, while demand continues to grow year after year.

By integrating renewable energy sources, i.e., distributed energy resources (DERs), traditional distribution networks, which are typically passive, are transformed into active ones. This means that in addition to demand, which characterizes traditional (passive) distribution networks, active distribution networks are also characterized by electricity production. It is important to emphasize that parts of the active distribution network (microgrids), in addition to operating in parallel with the rest of the system, can also operate independently in so-called "island mode." There are a lot of published definitions of a microgrids, but most commonly used is the definition published by United States Department of Energy, which states: “Microgrid represents a group of connected loads and DERs in terms of clearly defined electrical boundaries which functions as one controllable unit in comparison to the main grid and which can work in two operational modes: grid-connected and islanded”.

The primary motivation for integrating DERs into the distribution network and forming microgrids lies in several key factors. In recent years, modern microgrids have been associated with the concept of the three Ds—decarbonization, decentralization, and digitalization.

The first reason is reducing harmful gas emissions during electricity generation (decarbonization), thereby preserving the environment. The second is local electricity generation (decentralization), which decreases transmission losses and enhances grid resilience. The third key factor is digitalization, which enables advanced monitoring, automation and optimization of power flow, improving overall system efficiency and reliability.

Additionally, economic factors can sometimes play a role. For example, if a city's development outpaces initial projections, increased electricity demand may require upgrading the distribution infrastructure, such as installing higher-capacity cables. In some cases, it may be more cost-effective in the long run to establish a microgrid. During peak demand periods, the microgrid can switch to island mode, reducing the load on the rest of the system while leveraging digital technologies for optimal energy management.

The following text will briefly address the architecture, types of microgrids, communication within microgrids, improved DER models for short circuit calculation and relay protection coordination, as well as current developments and challenges that need to be overcome [1-3].

II MICROGRID ARCHITECTURE

Understanding the main components of the microgrid is crucial for analyzing the behavior of the microgrid in both grid-connected and islanded modes. Figure 1 shows schematic representation of main components which are addressed in the text below.

Generation systems

This system, within the microgrid, consists of different generation units, such as natural gas generator, units that combine thermal and electrical energy (District Heating Plant) as well as different DERs such as photovoltaic systems, wind turbines, mini hydropower plants and etc. DERs that are the least harmful to the environment and have no emissions of harmful gases, making them the most attractive options, photovoltaic systems, wind turbines and mini hydropower plants [4].

PV systems generate electricity from sunlight, a plentiful and renewable resource. Their performance depends on location-specific factors such as solar intensity, cloud cover and temperature and system efficiency, including PV modules, DC-DC converters, and inverters with control mechanisms. Over time, PV system efficiency degrades due to fluctuations in solar input and converter performance. These systems are connected to the grid through power electronic devices [1].

A wind energy conversion system transforms wind energy into electricity and consists of mechanical and electrical components. The mechanical part extracts rotational energy from the wind, while the electrical part converts it into electricity. Key components include the tower, rotor, and nacelle, which houses the generator and gearbox. The rotor blades capture wind energy, transferring it to the generator via the gearbox, ultimately producing electrical power. Wind turbines can be partially or fully connected to the grid through power electronic devices [1].

Mini hydro generates electricity from flowing water, relying on local topography and annual precipitation. Without significant water storage, generation fluctuates due to uneven rainfall. Run-of-river systems, commonly used in mini hydro, divert a portion of river water through a channel or pipeline to a turbine or water wheel. The shaft's motion can drive mechanical systems like water pumps or generate electricity via a connected generator. Mini hydro operates similar to conventional hydro plants, but not all mini hydro power plants have water reservoir [1].

Energy storage system (ESS)

This system conducts several functions within the microgrid, such as: securing the quality of distributed electrical energy, reduction of daily peaks of consumption, frequency regulation, microgrid costs optimising etc. The most recognizable ESS are battery systems and flywheels [4, 5].

Batteries store energy chemically during charging and discharge it as electricity when connected to a load. In an microgrid system, storage can be mounted on the DC bus of each micro-source or used as a central system. Batteries are relatively cheaper than other storage devices and can reserve energy for future demand, making them a popular choice for microgrid storage. It is known that accumulator batteries generate DC voltage with a low amplitude. Therefore, they must be connected to the distribution network through power electronic devices, specifically inverters. The voltage amplitude needs to be increased to the level required by the grid, and then the DC voltage is converted to AC. It is important to note that the inverter connecting the batteries to the grid must be bidirectional to allow proper charging and discharging of the battery via the grid [6].

The operation of flywheels is based on the law of energy conservation, converting kinetic energy into electrical energy and vice versa. When there is excess electrical energy in the grid, flywheels store it as kinetic energy in rotating masses. The conversion is done using electromechanical machines like permanent magnet synchronous machines, asynchronous machines, and others. Losses occur due to friction during the operation of the rotating parts, and speed decreases during discharge or increases during charging. This presents a major drawback of flywheels as a type of distributed energy storage. Speed changes must be synchronized with the grid frequency, which is why flywheels must be connected to the grid using power electronic devices to match voltage amplitude and frequency with grid requirements [6].

Supervisory and control system

This system provides smart control using the communication protocols. It controls electrical generation of all units within the microgrid, which is remote-controllable and it controls the operating state of all switch gear based on economy and reliability criteria [4, 5].

Loads

Within the microgrid, in most cases, two types of loads can be found. Critical loads that need to be constantly supplied and other that can be used for power balance among generation units and loads, accomplishing optimal production of electrical energy [4, 5].

Microgrid controller

Controller supervises current operation of a microgrid and communicates with other controllers integrated in production units, such as inverter-based controller. These controllers can communicate with higher levels of control, such as ADMS (Advanced Distribution Management System) and DERMS (DER Management System) [4].

Point of common coupling (PCC)

PCC is a key component, because it operates as a physical connection between microgrid and the grid to which it is connected. It serves as an interface where the electrical energy is exchanged between these two systems. PCC consists of switches, relay protection devices and synchronisation equipment. Voltage magnitude and frequency are continuously measured on the PPC, ensuring seamless connection and disconnection of the microgrid from the rest of the distribution system [1, 5, 7].

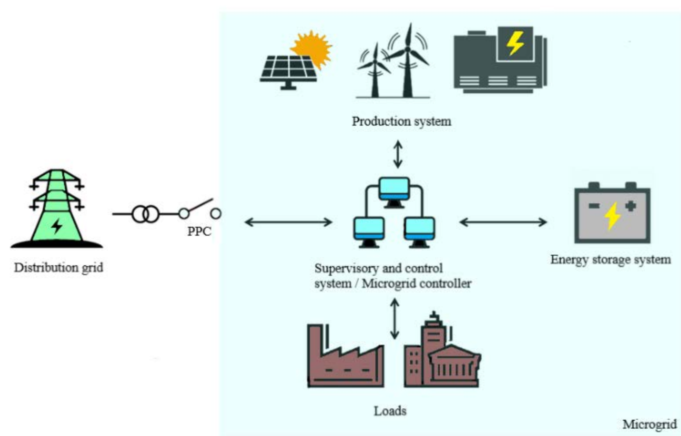

Figure 1. Schematic representation of microgrid components [8]

When discussing microgrid architecture, it is important to consider the scenario where multiple microgrids operate within a distribution network. This concept is known as networking microgrids.

In general, a microgrid can operate in two modes: grid-connected and islanded. However, when microgrids are networked, a third mode, networking mode, emerges. In this mode, microgrids are not only connected to the system through the PPC but are also interconnected with each other via the PPC. This represents a scenario where microgrids are disconnected from the main system but form a larger interconnected island.

In systems with networking microgrids, mutual communication is essential for optimizing energy exchange, efficiently utilizing DERs, and maintaining voltage and frequency within specified limits. This concept enhances security, reliability, and the quality of the electricity supply, but it also requires complex communication and control mechanisms [7].

III Types of Microgrids

Since term “microgrid” is relatively new in power systems, there is not a specified classification of them. However, differences among microgrids can be observed based on their connection method to the grid, control strategy, size, power supply method, type of generation units, location and application. In further text, these differences will be briefly addressed.

Connection method to the grid: If a single building (residential, commercial, hospitals, hotel…) has at least one DER integrated and has the ability to switch into an islanded mode, this building is an elementary level microgrid. The next (medium) level would be a few buildings combined, like university and hospital campus or military base, that can also transition to islanded mode and supply itself using DERs. The highest level would be if a part of a distribution grid supplied by DERs can transition to islanded mode of operation and function seamlessly like and system of its own [9].

Control strategy: Two types of control strategies can be distinguished; centralized and decentralized, which will be addressed thoroughly later in text.

Size: This classification is determined by the nominal power of the production units within the microgrid. If the production capacity is up to 10MW, microgrid is considered small, if it is between 10MW and 100MW it is considered medium sized and finally it is 100MW or more it can be labeled as big [10].

Power supply method: Depending on the specific requirements, electrical energy is utilized in both alternating (AC) and direct (DC) forms. AC is primarily used for transmission, distribution, and powering the majority of everyday devices. On the other hand, DC is employed to power certain electronic devices and, in some cases, for transmission, most commonly in interconnections. As a result, microgrids can be classified into DC, AC with frequencies of 50 or 60 Hz, hybrid form and high-frequency AC, typically around 500 Hz. This classification will be briefly addressed in the following text [11, 12]:

DC microgrids are those in which generation units produce DC voltage that supplies loads that require DC voltage. The advantage of DC microgrids over AC is that synchronization is not required and power quality problems are rare. Additionally, costs are reduced because there is no need for inverter units (except on PPC for connection to the AC grid). Furthermore, higher harmonics and leakage currents do not exist in DC microgrids, but the downside is that the protection within DC microgrids is extremely complicated. They are used in telecommunications, electric vehicles, data centers, etc. [11, 12].

AC microgrids (50Hz and 60Hz) are the most common, and they will be the focus of this article. DERs that generate DC voltage are connected to the system through inverters, which convert the direct current into alternating current of a specific frequency. When such a system includes DC consumers, a rectifier is installed at their connection point to ensure a reliable power supply for DC devices [11, 12].

Hybrid microgrid combines sections operating as AC systems with those functioning as DC systems, allowing both AC and DC consumers to coexist. This setup gives users the flexibility to connect to either AC or DC power based on their needs. Power electronic devices separate the AC and DC components, which can reduce the need for additional synchronization equipment. However, this configuration does not guarantee lower energy losses, as inefficiencies in converters, line losses, and transformer losses may still occur. Hybrid microgrids also require [11, 12].

A concept that is still under research involves microgrids operating in AC mode at a frequency of approximately 500 Hz. Using power electronic devices, the DC voltage generated by DERs is converted into high-frequency AC voltage and transmitted through the network to consumers. At the consumer's end, an AC/AC converter transforms the 500 Hz voltage into 50 Hz voltage for delivery. The benefits of using this approach are: high-frequency voltage reduces harmonic distortion, improvement of efficiency by lowering voltage ripple in electrical machines and allowing transformers and other passive system elements to be more compact. Additionally, distributed generators can more easily connect to flywheels and other energy storage systems. The drawbacks, on the other hand lie in the fact that high-frequency operation increases the series impedance of components, leading to higher voltage drops along the lines. Cable cross sections are also more significant compared to 50 Hz systems, making long-distance transmission less cost-effective. Moreover, control and communication devices are more complex due to the challenges of working with high frequencies [1, 11].

Type of generation units: Based on the origin of the driving force used for the electricity generation, three types of generation units can be distinguished. The first category is microgrids that use energy from renewable energy sources, such as solar, wind, bio masses and hydro. Benefits coming from this type of microgrids are that the pollution and carbonization due to electricity production is reduced to a minimum. That is the reason why these types of microgrids become more and more popular. On the other hand, intermittent operation of those generation units presents a challenge, especially in islanded mode of operation, where ESS is mandatory. The second type are microgrids powered by generation units using fossil fuels, which are, in most cases, diesel or natural gas generators. Throughout the years, these were the only types of local generation, until renewable energy sources were implemented. The third type represents hybrid type in which renewable generation units as well as fossil fuel generation units can be found [13].

Location: Microgrids that are located within a bigger distribution grid or are connected to it with PCC, are classified in available or localized microgrids [14]. They can operate in grid-connected, as well as in an islanded mode of operation. Remote microgrids, alternatively, are formed in geographically unavailable locations; meaning the distribution network do not serve those locations. Consequently, remote microgrids operate exclusively in islanded mode. Remote military bases, certain mountain villages, islands in the middle of the ocean, etc. [15].

Application: Microgrids can be divided into several types based on their application, for example: residential microgrids having only households as loads; industrial microgrids; commercial microgrids like airports, hospitals, data centers, malls etc.; military microgrids; university microgrids and other smaller classifications [16].

IV Control Strategies Within Microgrid

In terms of microgrid control (such as energy flow, switching states, generator engagement, etc.), two fundamentally different approaches are commonly distinguished: centralized and decentralized.

Centralized control relies on collecting data from system elements into a single central control unit. Once the data is gathered, the central unit processes the information and assigns tasks to the controlled units. In this approach, communication between the controlled units and the central unit must be fast, reliable, and accurate [17-19].

In decentralized control, each unit is controlled by its local controller, which collects data locally. These controllers operate independently and are not fully aware of the system state or the operation of other local controllers [17-19].

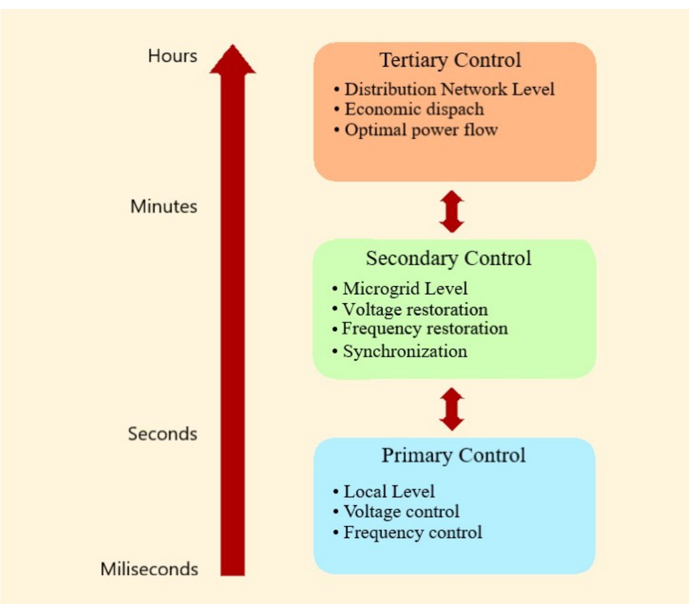

Figure 2. Schematic of hierarchical control in microgrids [7]

In cases involving large-scale interconnections spanning extensive geographical areas, centralized control can become impractical due to the need for constant communication between controlled units and the central controller. Similarly, decentralized control may not be optimal due to a lack of communication between local controllers, despite the crucial interdependence of system components. This leads to a compromise solution: hierarchical control system. This system consists of three levels: primary, secondary, and tertiary. These three levels of control are described in the following text and schematically illustrated in Figure 2. This control structure is based on descending characteristics: active power-voltage, reactive power-frequency, and for DC microgrids, DC power-voltage.

Primary Control: The first level of control in the hierarchical system occurs locally, with the fastest response time compared to the other two levels. It relies exclusively on local measurements and does not require communication. Similar to primary regulation in transmission networks, primary control uses the characteristics mentioned above to prevent system collapse (such as frequency or voltage drops below permissible limits). The goal of primary control is to quickly halt frequency and/or voltage drops. Once primary control has been completed, secondary control follows [17-19].

Secondary Control: After primary control is completed and a short delay, secondary control is implemented. The primary goal of secondary control is to engage generation units (Unit Commitment) to restore frequency and voltage to their nominal values. Although we described a scenario where system imbalances occur, hierarchical management is constantly active, especially in islanded mode. When consumers are connected or disconnected from the grid, significant voltage and frequency deviations from nominal values may occur, requiring constant monitoring [17-19].

Tertiary Control: Tertiary control refers to optimization in a broader sense. This includes finding the optimal generation unit commitment, calculating optimal power flows, and forecasting load demands. While primary and secondary control operate on a local level, tertiary control operates across the entire distribution network, including the microgrid. Tertiary control typically begins on a timescale of minutes, whereas primary control operates in milliseconds. This time difference is due to the need for feedback from the rest of the system to calculate optimal generation commitments and power flows, rather than relying solely on the microgrid [17-19].

Every DER connected to the grid via power electronics device (inverter) has an integrated control strategy. This control strategy dictates how the DER will act depending on the state of the grid, whether it is in normal or fault condition, and in microgrids, whether it is in grid-connected or islanded mode of operation. Four control strategies can be distinguished:

Grid-forming: In this mode, DER behaves as voltage source, with certain magnitude and frequency.

Grid-supporting/grid-forming: This mode is used mostly when the microgrid works as an island. DER behaves as a voltage source with variable voltage magnitude and frequency. These values are determined based on droop characteristics. This mode is very valuable because in islanded mode DERs are the only sources of electrical power. These types of DERs usually have

VSM (Virtual Synchronous Machine) technology implemented. Due to the absence of synchronous generators within the microgrid the systems lack inertia. This technology is essential as it provides an output voltage waveform that mimics that of a synchronous generator.

Grid-following: In this mode, DER acts like a current source. This strategy is used with DERs that have intermittent output power, for example PV arrays, so that maximal output power can be utilized. They usually use function like MPPT (Maximum Power Point Tracking).

Grid-supporting/grid-following: In this mode, DER acts also like a current source, the only difference is that is suitable for parallel connection of DERs with droop characteristics [20].

"Grid-following" and "Grid-supporting/grid-following" controls do not require additional current limitation mechanisms to protect power electronics devices, as they directly regulate the current. When the fault occurs, these DER systems inject predefined values of the direct, and sometimes inverse, fault current components.

On the contrary, “Grid-forming” and “Grid-supporting/grid-forming” strategies, primary control output voltage, which can lead to a significant increase in current during a fault. Therefore, in DER systems with these implemented controls, current is limited to predefined values, slightly above nominal (usually 1.5 times the nominal current), to protect power electronics devices.

This means that regardless of the DER operating mode and the approach used for current limitation, every DER will, after a fault, limit the current it injects into the grid exactly as required by the Grid Code standard [20].

It is important to note that some DERs can seamlessly change their control strategies. Studies were conducted [21] in a real-time microgrid operating in islanded mode, where DERs switched between grid-supporting-grid-forming and grid-supporting-grid-following strategies. Voltage and current at the coupling nodes were analyzed, leading to an interesting conclusion: at the moment of the control strategy change, a slight variation in voltage and current occurred, but the overall system continued to operate seamlessly.

This is particularly important when transitioning from grid-connected to islanded mode. For example, consider a microgrid initially operating in grid-connected mode. Within this microgrid, three DERs function in grid-following mode because voltage and frequency stability are maintained by the main grid. However, when transitioning to islanded mode, at least one DER must switch to grid-supporting/grid-forming mode to regulate voltage and frequency around their nominal values, considering droop characteristics, total power demand, and transmission losses. The remaining DERs can either continue operating in grid-feeding mode or transition to grid-supporting-grid-following mode, depending on the DER and load types [20, 21].

V Communication Within Microgrid

Communication within the microgrid is crucial for establishing effective control strategies. Two types of communication can be distinguished and they are addressed in the following text.

Master-Slave Communication: Master-slave communication refers to the direct interaction between "slave" local controllers and one master controller within a microgrid. The master controller gathers data from all the slave devices and issues commands based on the processed data. If multiple interconnected microgrids exist, each microgrid’s master controller acts as a slave to the main master controller of the distribution network. In this case, the master controller of the distribution network collects data from each microgrid’s master controller, which then acts based on the data collected. This type of communication is commonly used in centralized or hierarchical management systems [7].

Publish-Subscribe Communication: Publish-subscribe communication is an indirect form of communication. Each controller within the microgrid publishes specific data and subscribes to data published by other controllers. Likewise, each microgrid publishes and reads data to and from the distribution network. Although there is still a master controller in the distribution network to initiate communication with microgrid controllers, the exchange of data between microgrids is indirect through the publish-subscribe mechanism [7].

The advantage of this communication model is that all controller data is immediately available, allowing for the seamless integration of new microgrids into the system ("plug and play"). This approach reduces complexity and enhances flexibility in incorporating new microgrids into the system. Publish-subscribe communication is typical of decentralized management systems.

VI Short-Circuit Calculation and Relay Protection in Microgrids

Relay protection in traditional distribution networks has already been well established and performs well in most cases. Distribution network, in most scenarios, has radial configuration, hence most of the protection used is delayed and instantaneous overcurrent protection. Another important term about these types of protection is selectivity level. It represents time delay between two neighboring relays on same feeder; in other words, the further the protection device is from the source node of the distribution network, less time for tripping is needed. If well calibrated, the whole system would function seamlessly. If a loop in configuration is found, directional overcurrent protection must be installed and again selectivity must be maintained.

In the text above, it was briefly described, how relay protection functions in traditional distribution networks. Here, electrical energy is distributed in one direction, from the source node to the lower layers of the distribution network where loads are located.

By integrating DERs in distribution networks, certain benefits have been achieved, but new challenges have also arisen. Some of the benefits were discussed in introduction, as for the challenges, two main ones are the short circuit calculation and relay protection calibration. First step in resolving those challenges is introducing new, improved DER models.

DERs such as PV arrays, wind turbines, ESS and others are connected to the grid via power electronics device - inverter. With regards to wind turbines, two types can be distinguished, those are DFIM (Doubly Fed Induction Machine) and IBDER

(Inverter Based DER). The first one is partially connected to the grid via power electronics device and the second one is directly coupled using a power converter. When the short circuit occurs, based on the location of the fault, DFIM can be separated from the grid by the protection device within the DFIM to protect the inverter unit and continue to function as an induction machine. On the other hand, if the fault is further away and inverter unit cannot be damaged, the output current can still be controlled and DFIM will stay connected to the grid. This is the case if the DFIM is protected by crowbar, which is a three-phase resistor. The more expensive solution is to use power electronics device called chopper, that can maintain the control over the output current, regardless of fault location. Finally, IBDER is fully connected to the grid via power electronics device, which means when the fault occurs, it will stay connected to the grid. That being said, in further text only DFIMs protected by choppers and IBDERs will be analyzed since these types of wind turbines are most commonly used in both, scientific research and industrial applications. PV arrays and ESS act as a IBDERs, so in further text DFIMs protected by chopper, IBDERs, PV arrays and ESS will be addressed modeled as IDERs (Inverter DERs). As for the DFIM protected by crowbar, the term DFIM will be used [22].

According to standard IEC 60909, DFIMs should be modeled as an induction machine, despite fault location (these models were established long ago), but contribution to the total short circuit current is different. This can lead to inaccurate results, because during a short circuit induction machines contribute with 4 to 5 times their nominal current in comparison with inverters which contribute 1.5 times their nominal current. IDERs on the other hand should be modeled as a constant current source, with the current equal to the current limitation of the inverter in question. This approximation is good enough if distribution network has a few IDERs far away from the short circuit location. However, microgrids nowadays have a high penetration of IDERs so total short circuit current calculated according to the IEC 60909 would be a lot different from the real-time value [22].

Consequently, short circuit study on a real time microgrid was conducted [23], and it was concluded that IEC 60909 models must be upgraded. New models, unlike the IEC 60909, take Grid Code Standard into an account. This standard states how to safely integrate DERs into the grid, keeping network operation intact. Two requirements stand out from the Grid Code standard and are crucial for developing upgraded models of DFIMs and IDERs. Those two requirements are Low Voltage Ride Through (LVRT) and Reactive Current Injection (RCI) [23, 24].

During the short circuit mode of operation, voltage magnitudes in network nodes decrease drastically. The closer the node is to the fault location, the voltage decrease is more significant. The LVRT standard determines for how long, after the occurrence of short circuit, DER must stay connected to the grid, depending on the voltage drop at the coupling node. The more significant the drop, the shorter period of time DER must stay connected. On the contrary, at the beginning of integration of DERs into the distribution network, DERs would be momentarily disconnected from the grid when short circuit or voltage drops occurred. The necessity of introducing LVRT standard lies in the fact that nowadays distribution networks are highly penetrated with IBDERs and disconnecting them during faults or voltage drops would cause problems related to system stability [23, 24].

Equally important is the RCI standard. Based on the voltage drop in the coupling node of IDER, the RCI standard would determine how much reactive current must be injected to the grid. The higher the voltage drop, the higher the reactive component of the total injected current.

When those two standards are used and the fault occurs, if the voltage drop during short circuit is beyond acceptable limits, connection time of IBDER to the grid, as well as the reactive component of injected current is calculated. This is especially important in microgrids islanded mode, where DERs are the main source of power.

VII Developments and Challenges

As previously mentioned, in the past few decades, many developed countries have been modernizing their electrical systems by implementing DERs and forming microgrids. However, like any development that brings benefits, this also comes with new challenges. In this paragraph, challenges that come with concept of microgrids will be addressed.

- Legal uncertainty: Microgrids face two key legal challenges. Firstly, whether they are classified as electrical distribution utilities subject to state regulation and second, if exempt, how they fit into existing legal frameworks for electricity generation, sale, and distribution. A clear legal identity is crucial to ensure regulatory certainty, making microgrid projects financially viable. Without this, the risks and uncertainties may outweigh potential benefits. Several states in the U.S. have analyzed microgrids within current electricity laws, providing valuable insights into the evolving regulatory landscape [25].
- Regulatory uncertainty: Since a microgrid is relatively new term in power systems engineering, technical development went ahead of the regulatory framework. A microgrid may be considered an electric corporation if it serves multiple customers, transmits electricity across public roads, or has a franchise from local authorities. If classified as a utility, it may face regulations on pricing, construction, and service obligations. Microgrids using public roads need local approval, but if an existing utility has an exclusive franchise, new microgrids may be restricted. In some cases, like in New York, non-exclusive franchises require a competitive process. Most microgrids are not fully regulated as utilities, but legal decisions vary. Those selling electricity must follow consumer protection laws, while those using combustion-based power must meet emissions regulations. Regulatory uncertainty remains a key challenge for microgrid development [25].
- Stability issues: The stability of the system can be compromised by the high penetration of DERs, as uncertainties in major power sources (such as PV and wind turbines) can cause frequent imbalances between generation and consumption, due to their intermittent operation. These uncertainties can lead to serious

frequency and voltage stability issues in microgrids, making them more vulnerable than traditional power systems. Additionally, voltage and frequency oscillations at the local level may arise due to the interaction of control systems of distributed generators, requiring a detailed stability analysis for small disturbances. To address these issues, the development of advanced control systems based on fast-acting power electronics can be effective. Transient stability analysis is also necessary to ensure smooth transitions between grid-connected and island operating modes. In the future, the integration of ESS will be essential to improve system stability, alongside the incorporation of distributed generators [7].

- Ownership challenges: Microgrids can be classified into three types based on ownership: utility, community, and private. Privacy concerns are particularly important for private and community microgrids, as not all owners may wish to share all information except for power exchange details. Various data related to these microgrids must be handled with care. These types of microgrids can function as a source or sink of electrical power. When solving economic dispatch at the higher control level, special attention is required when dealing with these microgrids. On the other hand, utility microgrids are fully flexible and can actively participate in optimal energy management during both normal and emergency conditions [7, 25].
- Threat of a cyber-attack: Microgrids use various information and communication technologies, making them vulnerable to cyber-attacks that could disrupt operations. In centralized control schemes, the central entity processes data and broadcasts control commands, offering global situational awareness that enhances resistance to cyber threats. However, distributed control schemes rely on local controllers with access to partial data, increasing their vulnerability to attacks. Malicious entities can corrupt data by targeting nodes or communication links, threatening system stability. High computation, communication, and power electronics-based controllers are particularly susceptible to cyber threats, with reports of false data injections disrupting inverter synchronization. As networked microgrids grow, the risk of severe cyber-attacks increases, necessitating effective safeguards and further research [7].
- Low inertia system: In conventional power systems, the presence of numerous synchronous generators and their rotating masses provides significant inertia. Inertia is crucial for maintaining frequency at its nominal level, as the kinetic energy of these masses helps stabilize frequency fluctuations in the event of an imbalance (primary and secondary regulation). Conversely, microgrids with a large number of DERs connected to the network via inverters have significantly lower inertia. This can be a major challenge, especially in islanded operation mode, where the microgrid effectively becomes a low-inertia system due to the lack of rotating masses. While a definitive solution has yet to be established, certain control mechanisms, such as Virtual Synchronous Machines (VSM), can contribute to improved stability. VSM technology emulates the characteristics of synchronous generators, providing artificial inertia to the system and helping to stabilize frequency fluctuations. The integration of flywheels alongside VSM can further enhance stability, especially in islanded modes, by acting as energy storage that responds quickly to frequency deviations [26, 27].
- EV integration*:* The integration of electric vehicle chargers into microgrids is an area that requires thorough research. An electric vehicle connected to a charger within a microgrid acts as a consumer when in charging mode. However, if it operates in discharging mode, it can supply its stored energy to the microgrid, effectively functioning as a generation unit. This new concept is called vehicle to grid (V2G). Furthermore, in the event of a short circuit within the microgrid, the electric vehicle becomes an additional source contributing to the fault current and influencing its distribution across the microgrid [28].
- Relay protection setting: When it comes to setting and calibration of relay protection in microgrids, we are encountering few obstacles. Firstly, short circuit current (for the same fault type and location) can have up to 11 times lower value in islanded mode then in grid-connected [6]. In the islanded mode, short circuit location is powered solely by DERs, therefore fault can't be detected if the relay protection stays calibrated for the grid-connected short circuit values. Consequently, relay protection must be adaptive, able to switch between operating modes and successfully trip when the fault occurs in both operating modes. Secondly, direction of the power flow, as previously said, is downstream, from the source node to the end loads, both in normal operating conditions and during a short circuit condition. However, high penetration of DERs along the feeders of distribution network causes the scenario where the fault location is powered from two sides, so there is a bidirectional power flow. Consequently, traditional relay protection such as overcurrent protection cannot be used. During a fault, the inverter reduces the voltage magnitude at its terminals, making undervoltage protection a potential solution for fault detection. However, a significant issue arises: in microgrids, especially in islanded mode, voltage drops can occur due to load fluctuations and battery state of charge variations. This makes it difficult to design a protection system capable of distinguishing between voltage drops caused by load changes and those caused by actual faults. An improved version of undervoltage protection is superimposed undervoltage protection or filtered undervoltage protection. This protection operates similarly to standard undervoltage protection but is less sensitive to slow voltage changes resulting from load variations. However, adding these additional features increases the cost of the protection system. It is important to note that sudden changes in battery state of charge can also cause rapid and significant voltage drops, potentially triggering this type of protection. In the case of an unbalanced short circuit, DER will inject symmetrical

positive-sequence currents to stabilize the network voltage. However, the voltages at its terminals will remain unbalanced. This suggests that unbalanced faults can be detected using negative-sequence voltage relays, which will activate only in the presence of unbalanced faults. A clear limitation of this protection method is that it does not respond to three-phase short circuits. DERs are typically connected to the network through a DY transformer (where the Y is grounded on the high-voltage side). In the event of ground faults, the network will exhibit a zero-sequence current component, which originates from the network rather than from DERs. To detect ground faults, zero-sequence current relays can be installed on the high-voltage side of the DY transformer. However, this method is only effective for ground faults. During a fault, the network impedance changes independently of the fault current contributions from both DERs and traditional energy sources. Given this, tests can be conducted to determine the threshold impedance value present under fault conditions. Using this known threshold, a distance relay can be installed at the DER's connection point to the grid, measuring impedance variations. If the measured impedance drops below the predetermined threshold during a fault, the relay will activate. However, a key challenge with this approach is that short distribution lines within the microgrid can make it difficult to coordinate different relays or precisely define protection zones [6, 24, 29].

VIII Conclusion

Microgrids offer significant potential for enhancing energy efficiency, resilience, and the integration of renewable energy. In this paper we have discussed the core architecture of microgrids, various types and the essential control strategies that ensure their optimal performance. We also highlighted the importance of communication systems for real-time monitoring and the advancements in mathematical models of DERs that improve energy management, and in particular short circuit calculations and protection relaying studies.

Despite these advancements, challenges remain in terms of technical, regulatory, and economic barriers. Overcoming these challenges through ongoing developments in control algorithms, communication technologies and DER modeling is essential for realizing and achiving the full potential of microgrids.

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Mikromreže - trenutni razvoj i izazovi

Rezime *- U poslednjim decenijama, koncept mikromreža postao je ključna komponenta u modernizaciji električnih sistema, posebno u razvijenim zemljama. Mikromreže omogućavaju integraciju distribuiranih energetskih resursa, kao što su obnovljivi izvori energije (solarni paneli, vetroturbine) i sistema za skladištenje energije, u postojeće distributivne mreže. Ovaj pristup pruža veću efikasnost, fleksibilnost i otpornost na prekide u napajanju energijom, a istovremeno smanjuje štetne emisije. Međutim, dok mikromreže nude brojne prednosti, one takođe predstavljaju niz izazova i pitanja u vezi sa tehničkim, regulatornim i ekonomskim aspektima njihove implementacije. Tehnički izazovi uključuju optimizaciju rada mikromreže u realnom vremenu, upravljanje potrošnjom i proizvodnjom energije i obezbeđivanje stabilnosti mreže u uslovima varijabilnosti obnovljivih izvora energije. Regulatorni okvir i modeli tržišta energije takođe moraju da evoluiraju kako bi podržali integraciju mikromreža i obezbedili fer tržišno okruženje. Ovaj rad istražuje ključne izazove u vezi sa razvojem mikromreža, kao i otvorena pitanja koja još uvek čekaju odgovore kako bi se omogućilo njihovo široko primenjivanje i optimalno funkcionisanje.*

Ključne reči *- distribuirani energetski resursi (DER), mikromreže, strategije upravljanja unutar mikromreža, DER modeli*