# Electrical Protection Systems for the Evolving Microgrid Environment

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*Abstract: This article explores the vital aspects of grid protection within the context of microgrids, focusing on current grid protection techniques. As microgrids gain prominence in the modern energy landscape, the need for effective protection measures becomes increasingly critical. The article delves into the fundamentals of relay protection and its role in safeguarding microgrid assets. To provide a comprehensive understanding of these protection methods, the article uses simulation models in Simulink, offering insights into the impact of various sources of electrical energy on the grid, as well as providing simulated protection models within microgrid systems. Through highlighting the unique challenges and considerations associated with grid protection in microgrids, this article serves as a valuable resource for researchers, engineers, and practitioners striving to enhance the reliability and security of microgrid operations.*

*Keywords: protection system; fault management; microgrids; active distribution grids; digital protection relays*

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## 1 Introduction

The world of energy is undergoing a profound transformation, driven by the imperatives of sustainability, grid resilience, and the integration of renewable energy sources. In this rapidly evolving landscape, microgrids have emerged as a transformative solution, poised to reshape the way we generate, distribute, and consume electricity. With the growing integration of distributed energy resources (DERs) and the increasing penetration of renewable energy sources, the domains of microgrid operation and protection have taken on paramount significance, shaping the present and future of our energy infrastructure [1]. The importance of microgrid protection and control strategies is evident in the works of various researchers. Shah and Gole (2016) provide an overview of microgrid protection and control strategies [2]. Guerrero et al. (2013) focus on distributed control for the management of energy storage systems in islanded microgrids [3]. Similarly, Katiraei and Iravani (2005) delve into power management strategies for microgrids with multiple distributed generation units [4]. Several studies contribute to the understanding of protection issues in microgrids. Akhavan-Hejazi and Fotuhi-Firuzabad (2012) conduct a comprehensive review of microgrid protection [8], and Behl and Tari (2015) offer a review of protection issues in microgrids [9]. Moradikordalivand and Saeed (2014) specifically review microgrid protection and islanding detection methods [10], while Moradikordalivand and Saeed (2017) explore detection and protection in microgrids using synchrophasor technology [11]. Vittal and Rajapakse (2013) focus on overcurrent protection for a microgrid system [12]. Research on fault detection and protection mechanisms in microgrids is addressed by various authors. Rosas-Caro et al. (2016) present fault detection and protection of microgrids based on current and voltage phasor measurements [13], and Etemadi and Vittal (2014) discuss optimal protection coordination of microgrids considering voltage-controlled distributed generators [14]. Liu et al. (2015) contribute with improved overcurrent protection coordination for microgrids with high-penetration distributed generation [15]. The impact of photovoltaic systems on grid interconnection and overcurrent protection coordination is explored by Mekhilef and Salam (2014) [16]. Additionally, Jiménez-Estevez et al. (2014) provide an overview of microgrid protection systems [17]. Control strategies for microgrids in both grid-connected and islanded modes are discussed by Caire and Guerrero (2019) [18]. Meanwhile, Ul Haq et al. (2015) review islanding detection methods for distributed generation [19]. Further insights into overcurrent protection coordination in microgrids are provided by Schinabeck and Almassalkhi (2016) [20]. Additionally, Štefko et al. (2021) present a case study of power plants in the Slovak Republic and the construction of a microgrid and smart grid [21], while Manson and McCullough (2021) discuss practical microgrid protection solutions [22]. The modeling of protection relays and renewable energy sources for microgrid systems is addressed by Štefko et al. (2022) [23], and Štefko (2022) delves into the parameterization of protective relays in power systems [24]. Furthermore, technical manuals for specific protective relays are referenced, including ABB's REF-615 [25] and SEL-351A [26]. The comprehensive review and research presented in these articles contribute significantly to the understanding and development of microgrid operation and protection strategies, essential for the advancement of sustainable and resilient energy infrastructures.

**The Microgrid protection:** While the efficient operation of microgrids is of paramount importance, it must be coupled with robust protection strategies to ensure grid reliability and security under various operating conditions [9]. The realm of microgrid protection encompasses a wide range of functions, including fault detection, isolation, and coordination [10]. In the face of dynamic grid configurations and the need for rapid responses, microgrid protection has taken on new dimensions. Adaptive protection strategies have emerged as a key area of focus in microgrid protection [9]. These strategies involve the development of protection schemes that can adapt to changing grid conditions and configurations. For example, as a microgrid transitions from grid-connected to islanded mode, protection systems must be able to reconfigure and adapt to the new operational context. Adaptive protection ensures that fault detection and isolation remain effective, even in evolving microgrid scenarios. Distributed protection systems have gained traction in microgrid protection as well [10]. These systems distribute protection functions across various devices within the microgrid, reducing the reliance on centralized protection schemes. Through decentralizing protection functions, microgrids can achieve a higher level of reliability and resilience. Fault detection and isolation can occur more rapidly and effectively when protection functions are distributed throughout the grid. This approach also enhances the overall cyberphysical security of the microgrid. The utilization of synchrophasor-based fault detection methods has also advanced the field of microgrid protection [11]. Synchrophasors are devices that measure voltage and current at a specific instant in time and provide highly accurate data for power system analysis. Through incorporating synchrophasors into microgrid protection systems, fault detection can occur with remarkable precision. This technology offers the ability to detect and isolate faults more quickly, contributing to the stability and reliability of microgrids.

# 2 The Impact of Various Power Sources on the Electrical Grid

The Currently, various software programs are available for simulating energy sources. This work will use the modelling environment MATLAB & Simulink, in which models of the most common types of energy sources have been created. When comparing models, we will consider photovoltaic systems, diesel generators, battery systems, thermal power plants, and hydroelectric power plants [19].

Simulated impact of Photovoltaic System on the Grid (modelled in Simulink): The model of the photovoltaic system was tested at a power of 100 kWp. The photovoltaic array consists of seven modules connected in series, which are parallel-connected into thirty-five strings. The electrical potential of the direct current is 480 V, and the output alternating current voltage from the inverter is 250 V, which is ultimately transformed to 22 kV through a step-up transformer. The simulated nominal current value was less than 3.75 A. The simulated fault current value stabilized at 5.62 A, with the highest peak fault current reaching 6.606 A. Simulated impact of Diesel generator on the Grid (modelled in Simulink): The model of the diesel generator was designed for direct connection to the grid. In this model, a synchronous machine was used for the generation of electrical energy. The rated current value was less than 3.73 A. The simulated value of fault current settled at 10.2 A. The highest peak fault current value near the source was 28.89 A. Simulated impact of Battery System on the grid (modeled in Simulink): The model of the battery energy storage system was based on the same principle as the photovoltaic system model. The model also uses a step-up transformer to feed electric energy into the grid. A battery module can be added to the photovoltaic system to mitigate fluctuations caused by weather conditions. The rated current value was less than 3.7 A. The simulated value of the fault current settled at 5.567 A. The highest peak fault current value near the source was 6.621 A. Simulated impact of Thermal power plant on the Grid (modeled in Simulink): The thermal power plant model is based on the same construction as the diesel generator model and is also designed for direct connection to the grid. In this model, a synchronous machine was used for the generation of electrical energy. The simulated rated current value was less than 3.72 A. The simulated fault current value stabilized at 27.15 A. The highest simulated peak fault current value near the source was 36.329 A. Simulated impact of Hydroelectric power plant on the Grid (modeled in Simulink): The hydroelectric power plant model is based on the same construction as the diesel generator and thermal power plant models. Similar to the previous models, it is designed for direct connection to the grid. In this model, a synchronous machine is used to generate electrical energy. The simulated rated current value was less than 3.723 A. The simulated fault current value stabilized at 12.8 A. The highest simulated peak fault current value near the source was 34.65 A [19].

## 2.1 Evaluation of the Impact of Various Sources and Description of Findings

From the simulated results, it is evident that the impact of different types of power plants, specifically models, significantly affects the electrical grid [19]. The use of numerous photovoltaic systems or battery systems can pose challenges in maintaining grid stability [14], while intelligent grids with a network breakdown feature can address these issues through the control of separated parts via a microgrid system [17]. Conversely, employing a combination of thermal and hydroelectric power plants complemented by diesel generators leads to a more stable grid [20]. Therefore, determining an appropriate combination of energy sources for microgrids is essential. Regarding the contribution of the inverter fault current Backfeed, it is noteworthy that the overall limit of the inverter fault current is calculated as the sum of the forward current component ($I_1$) and the backward current component ($I_2$) [25]. Inverters typically suppress currents with a non-rotating component ($I_0$), and the magnitude of the backward current component varies between inverters and generators [26]. While generators naturally provide a significant value of the backward current component, typically around 5 times the nominal current, inverters exhibit a magnitude of around 0.5 times the nominal current [26]. Most grid-interconnected inverters do not feed the backward current component into the grid, making it crucial for certain conventional protection methods, fault direction detection, and monitoring high-speed switching devices [20]. The backward current component effectively contributes to identifying unbalanced faults [26]. Addressing frequency tracking failures in inverters is crucial for power system stability. Some inverters that track the frequency of the power system may face challenges during faults, leading to waveform distortion and inaccurate frequency tracking [20]. In such cases, inverters may "guess" the grid frequency, causing instability and revenue losses. Inverters that do not rely on precise frequency tracking offer a more robust response [30]. However, it is acknowledged that certain inverters may behave erroneously even with the best protection system. Therefore, the industry is encouraged to use inverters with limited or no frequency tracking dependency, deviating from standards governed by grid parameters [20, 31]. As it is currently building more standards and regulations that will be followed when managing its facilities.

# 3 Design of a New Microgrid Protection System

## 3.1. Digital Protective Relay for Microgrids

Protection systems in the current scenario heavily rely on programmable protective relays that require configuration adjustments to adapt to changes in the system, ensuring the protection of the electrical grid and an uninterrupted power supply to consumers [20]. Digital programmable protective relays primarily serve protective and control functions for transmission and distribution lines, transformers, compensators, and other critical equipment characterized by high establishment costs [20]. These relays are equipped with user-programmable logic, synchronized measurements, data recording, fault recording, fast communication, and other protective functions [20]. The interdependence between control and protection is particularly pronounced in microgrid applications, where protective relays play a significantly amplified and crucial role compared to traditional systems [20]. In the context of microgrids, where the integration of renewable energy sources and distributed energy resources is prevalent, the role of protective relays extends beyond their conventional functions [5, 8, 15]. The advanced features of digital programmable protective relays contribute to the effective functioning of microgrid protection mechanisms, ensuring the robustness and reliability of these systems [20]. The ongoing research and advancements in this domain are essential to meet the evolving requirements of modern power systems [additional citation needed]. Moreover, the importance of protective relays in microgrids is underscored by the need for enhanced control and protection mechanisms to address the dynamic nature of microgrid configurations and changing operational conditions [2, 11]. As microgrids become increasingly integral to smart grids and resilient energy systems, protective relays play a pivotal role in maintaining grid stability and safeguarding against potential faults [7, 12, 18]. The comprehensive integration of protective relays in microgrid systems is a critical aspect of the broader research and development efforts aimed at shaping the future of energy infrastructure [1, 17, 20]. The advancements in protection technologies, guided by insights from ongoing research projects [7] [22], contribute to the overall adaptability and reliability of microgrid systems in diverse applications.

**Adaptive Protection System without Communication:** When the battery and photovoltaic systems on the distribution feeder are isolated by protection mechanisms, it triggers the islanded operation of the microgrid, accompanied by specific challenges [20]. For instance, during overloads or faults, the battery system produces a transient current of 120% of the rated current for 5 seconds, followed by a continuous current at the rated value. Simultaneously, the inverter voltage is maintained at a low-level, leading to an inverter disconnection after 5 seconds. When connected to the grid, the distribution network can generate fault currents at approximately eight times the rated current [20]. To address these challenges, it is imperative for digital protection systems to detect the status of control elements and dynamically adjust sensitivity settings to ensure network safety [20]. However, implementing this concept in practice poses challenges, particularly in fault location. The dilemma arises when increasing the sensitivity of protection, as it can result in a minimal difference between the fault current (the starting current of protection) and normal current or the starting currents of motors in industrial areas [20]. This underscores the need for continuous advancements in protection and control strategies in microgrid systems, as discussed in various research articles [2, 5, 8, 11, 15]. The research by Manson and McCullough emphasizes the practical solutions and challenges associated with microgrid protection, highlighting the promises and complexities in real-world applications [20]. Additionally, insights from ongoing research projects and reviews contribute to shaping effective protection mechanisms for microgrids [7, 9, 13, 18]. Furthermore, protection coordination in microgrids is crucial, especially considering the presence of distributed energy resources and the dynamic nature of microgrid configurations [12, 14]. The comprehensive understanding and implementation of protection strategies are vital for ensuring the reliability and stability of microgrid systems [20]. In summary, the challenges associated with islanded microgrid operation and protection underscore the importance of continuous research and development, incorporating insights from a variety of sources to enhance the effectiveness and adaptability of microgrid protection systems in practical scenarios.

In the power system of Slovakia, the predominant protection equipment for safeguarding power lines, devices, and the overall system comprises digital relays

[26]. These digital relays have progressively replaced outdated single-function protection devices, transitioning the power system towards modernization and improved performance [20]. Approximately 8.38% of outdated relays persist in the system, emphasizing the need for a comprehensive upgrade to digital programmable relays for effective transition towards smart grids [20]. To align with the evolving landscape and support the adoption of smart grids and microgrids, the replacement of outdated relays with digital programmable relays is imperative [20]. The integration of digital relays provides a broader range of functionalities, contributing to the flexibility and adaptability required in modern power systems [20]. Furthermore, insights from research articles, such as those by Lasseter [1], Shah and Gole [2], Guerrero et al. [3], and others [5, 15], underscore the importance of advanced protection strategies in the context of microgrid development. Protection coordination in microgrids, especially considering high-penetration distributed generation, requires careful consideration [12, 13, 16]. Manson and McCullough [20] provide a practical perspective on the promises and challenges associated with microgrid protection, emphasizing the need for robust solutions. In the context of the Slovak power system, compliance with distribution system requirements is crucial. The required settings for external network protection, as outlined in Table 1, should align seamlessly with the unique characteristics of the distribution system in Slovakia [30]. The ongoing research by Štefko et al. [19] and Manson and McCullough [20] sheds light on case studies, construction of microgrids, and the practical aspects of protection solutions in real-world applications, contributing to the body of knowledge in this field.

Table 1

The required settings for external grid protection in distribution grid Slovakia [22]

| Function of protection relay | Description | Starting value | Time delay action |
|---|---|---|---|
| The Undervoltage protection (U<) | Acts to switch off the circuit breaker in the event of a voltage drop. | 195,5 V | 0,1 s |
| The Overvoltage protection (U>) | Acts to switch off the circuit breaker in the event of a voltage surge. | 253 V | 0,1 s |
| The Under-frequency protection (f<) | Acts to switch off the circuit breaker when the frequency decreases. | 47,5 Hz | 0,1 s |
| The Over-frequency protection (f>) | Acts to switch off the circuit breaker when the frequency increases. | 51,5 Hz | 0,1 s |
| Delayed startup during initial power-up | Acts to switch on the circuit breaker when power is restored. | 230 V | 300 s |

### 3.1.4 Protective Relay Models

The models of individual protective relays were created in the Simulink program (v9.12.0.2039608, MathWorks, CA, USA), which is a part of the Matlab software. The selection of various types of protective relay models was based on their presence in distribution networks for voltage levels LV and MV. From the analysis of the occurrence of various types, standard output protections (overcurrent function and directional overcurrent function) were selected.

**Feeder relay protection:** For the feeder relay protection, we consider the first case, using only the overcurrent function for the first and second stages with the possibility of time delay. Alternatively, there's an option to use an additional stage as a warning state when the allowable nominal current value is exceeded. To simplify the setting of the overcurrent protection, a graphical user interface was created. The protection relay allows for setting the tripping characteristics according to IEC and IEEE standards, which can be applied to both the first and second stages. The slope of the characteristic curves can be easily adjusted using the pickup current, time multiplier, or delay, depending on the selected function. The model also provides the option to set the directionality for the overcurrent protection, which can be easily disabled.

The model of the outgoing protection consists of several modules available from the basic Simulink library, as shown in Figure 2. The protection algorithm is evaluated in the Time Relay Function module, and its output is compared to the simulation time based on the set tripping time. When the protection direction is activated (forward or reverse), the protection evaluates the direction based on the phase angle between voltage and current.

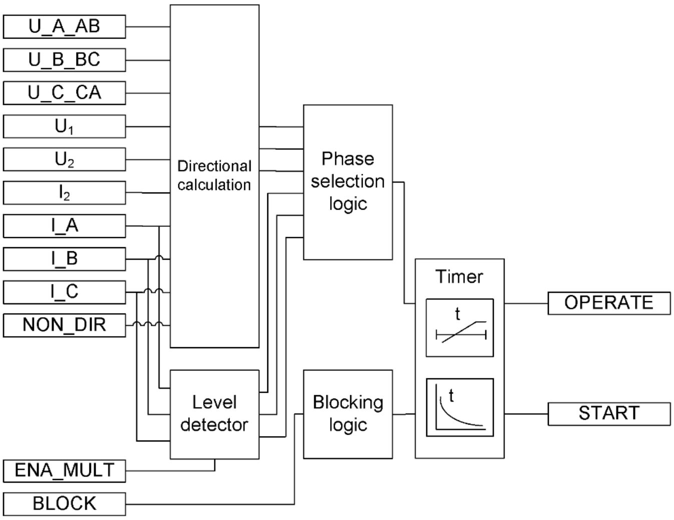

Figure 1

Diagram of the functionality module of the ABB REF-615 protection relay [25]

Protection and control using REF-615 relays from ABB are popular in various industrial sectors and distribution networks worldwide. For testing purposes, the functions "DPHHPDOC" and "DEFHPDEF" were employed. In the settings, the pickup current was set to 10 mA with a 40 ms time delay, using the inverse definite-time characteristic ("IDMT") [25]. The evaluation scheme for this function is depicted in Figure 2 for the REF-615 outgoing protection. To establish mutual communication between protective relays, modifications were made to the model itself. This included the addition of the "TRIP Logic" function, as shown in Figure 2. The mutual communication uses the GOOSE (Generic Object-Oriented Substation Events) message protocol with a timestamp.

**Directional feeder relay protection:** Due to the significant differences in the fault detection algorithm from the most common manufacturers, a new model of directional overcurrent relay from SEL has been created in the Simulink program. SEL has been gaining popularity in various applications in recent years, making it necessary for a better comparison.

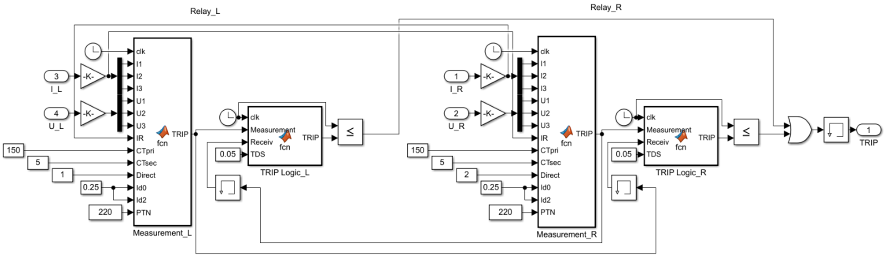

Figure 2

Model of feeder protections with mutual communication using the GOOSE protocol in the Simulink program

According to the results of the network operation analysis in the case of a ground fault, the non-rotating component of the fault current significantly increases, while the fault's negative sequence component changes simultaneously. This fact is notably considered in the fault detection algorithm shown in Figure 3. The function was added based on this, which improved the protection's performance in the tested fault condition. While during interphase faults, the subsequent and inverse components significantly increase, they are considered in a separate algorithm for better detection. The algorithm's logic determines the fault type from multiple methods and decides whether it is an interphase fault.

**Backup Protection System in Case of Protection Failure:** In case of protection relay failure, it is necessary for the backup system to take over the role of the faulty relay. Therefore, it is important to determine which relay should act in the event of such a failure. When considering the use of GOOSE communication between protection relays, it is desirable to design a backup protection system structure for such cases. In real-world applications of protective systems, this is typically done by the nearest protection relay associated with the protected equipment. In case of a protection failure to trip the breaker, the protection relay sends a "Breaker Failure" message, activating the backup protection relay to accurately locate the fault location. Such a system will be established for all considered protection relays throughout the tested topology.

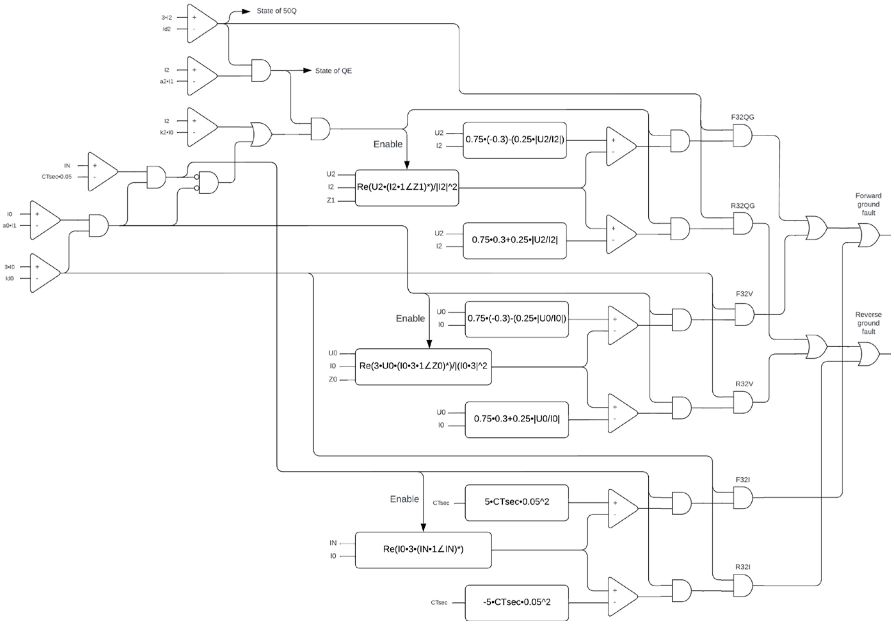

Figure 3
Simplified logic diagram of the directional OC protection SEL351A by SEL for ground fault types [26]

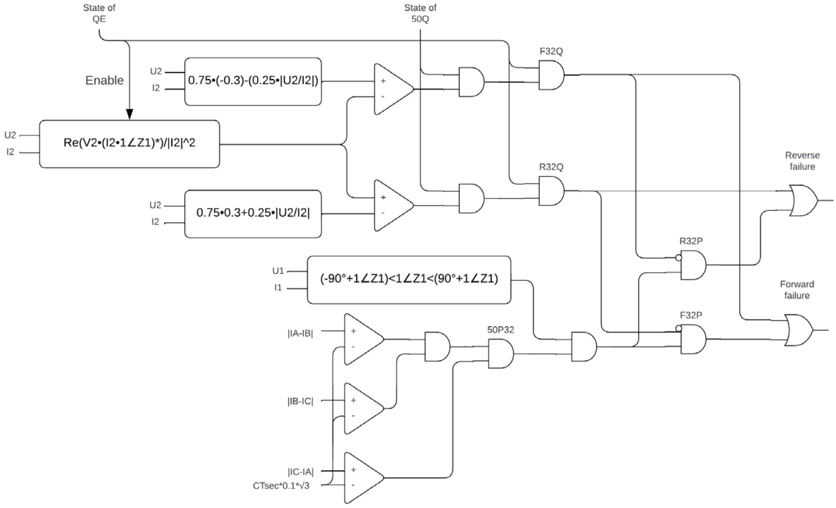

Figure 4
Simplified logic diagram of the directional OC protection SEL351A from SEL for interphase fault types [26]

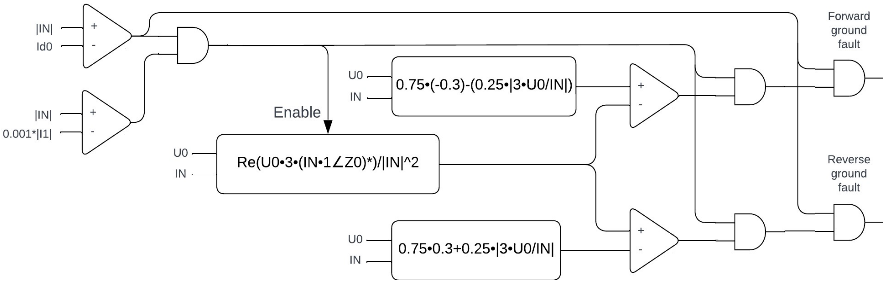

Figure 5
Simplified logical diagram of the directional OC protection SEL351A from SEL for ground faults in low-impedance grounded systems [26]

# 4 Design of Topology for Network Control using Current Protective Functions

To verify the functionality of the selected protective relays, a topology was created and tested using simulation in Matlab and Simulink software. For this reason, a testing topology for a microgrid was designed, considering various combinations of RES sources. Specifically, we chose the most widely deployed distributed sources of electrical energy from the currently ongoing or completed microgrid projects evaluated in the first chapter, where battery systems and photovoltaic power plants have the largest representation.

## 3.2. Fault Module

To parameterize various fault configuration states tested in the proposed topology, a basic fault module from the Simscape library for the Simulink program was used. Specific values for each type of fault state ranged from Ron values of 0.001 Ω to 100 Ω, while for Rg, we considered only two values, 10 Ω or 100 Ω.

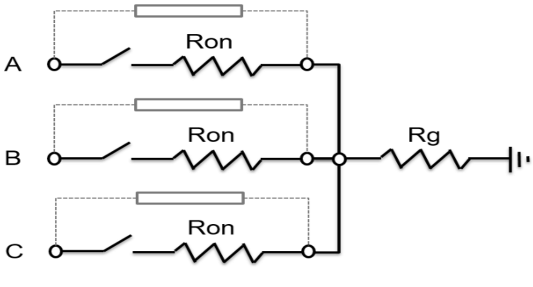

Figure 6
The Fault Model

Table 2
The required settings for external grid protection in distribution grid Slovakia [22]

| Line | Fault type | Impedance of the fault Ron | Impedance of the fault Rg | Forward action | Reverse action |
|---|---|---|---|---|---|
| V1 | L1-G | 0.001 Ω | 10 Ω a 100 Ω | P, Q, G a P | P, Q, G |
|  | L2-G | 0.001 Ω | 10 Ω a 100 Ω | P, Q, G a P | P, Q, G |
|  | L3-G | 0.001 Ω | 10 Ω a 100 Ω | P, Q, G a P | P, Q, G |
|  | L1-L2 | 10 Ω a 100 Ω | - | P, Q, G a P | P, Q, G |
|  | L1-L3 | 10 Ω a 100 Ω | - | P, Q, G a P | P, Q, G |
|  | L2-L3 | 10 Ω a 100 Ω | - | P, Q, G a P | P, Q, G |
|  | L1-L2-G | 0.001 Ω | 10 Ω a 100 Ω | P, Q, G | P, Q, G |
|  | L1-L3-G | 0.001 Ω | 10 Ω a 100 Ω | P, Q, G | P, Q, G |
|  | L2-L3-G | 0.001 Ω | 10 Ω a 100 Ω | P, Q, G | P, Q, G |
|  | L1-L2-L3 | 5 Ω a 50 Ω | - | P | P a - |
|  | L1-L2-L3-G | 5 Ω | 10 Ω a 100 Ω | P | P a - |
|  | L1-L2-L3-G | 50 Ω | 10 Ω a 100 Ω | P | - |
| V8 | L1-G | 0.001 Ω | 10 Ω a 100 Ω | P, Q, G | P, Q, G |
|  | L2-G | 0.001 Ω | 10 Ω a 100 Ω | P, Q, G | P, Q, G |
|  | L3-G | 0.001 Ω | 10 Ω a 100 Ω | P, Q, G | P, Q, G |
|  | L1-L2 | 10 Ω a 100 Ω | - | P, Q, G | P, Q, G |
|  | L1-L3 | 10 Ω a 100 Ω | - | P, Q, G | P, Q, G |
|  | L2-L3 | 10 Ω a 100 Ω | - | P, Q, G | P, Q, G |
|  | L1-L2-G | 0.001 Ω | 10 Ω a 100 Ω | P, Q, G | P, Q, G |
|  | L1-L3-G | 0.001 Ω | 10 Ω a 100 Ω | P, Q, G | P, Q, G |
|  | L2-L3-G | 0.001 Ω | 10 Ω a 100 Ω | P, Q, G | P, Q, G |
|  | L1-L2-L3 | 5 Ω a 50 Ω | - | P | P a P |
|  | L1-L2-L3-G | 5 Ω | 10 Ω a 100 Ω | P | P a P |
|  | L1-L2-L3-G | 50 Ω | 10 Ω a 100 Ω | P | P a P |

## 3.3. Microgrid Model

The topology of the microgrid consists of three radial networks and fourteen feeders, as shown in Figure 7 for the already created model in the Simulink program.

Furthermore, it comprises twelve electrical substations, where measurements and protective relays are installed to protect each feeder from both sides. The placement of distributed energy sources was selected for electrical station 2_6_7 and electrical station 9_10.

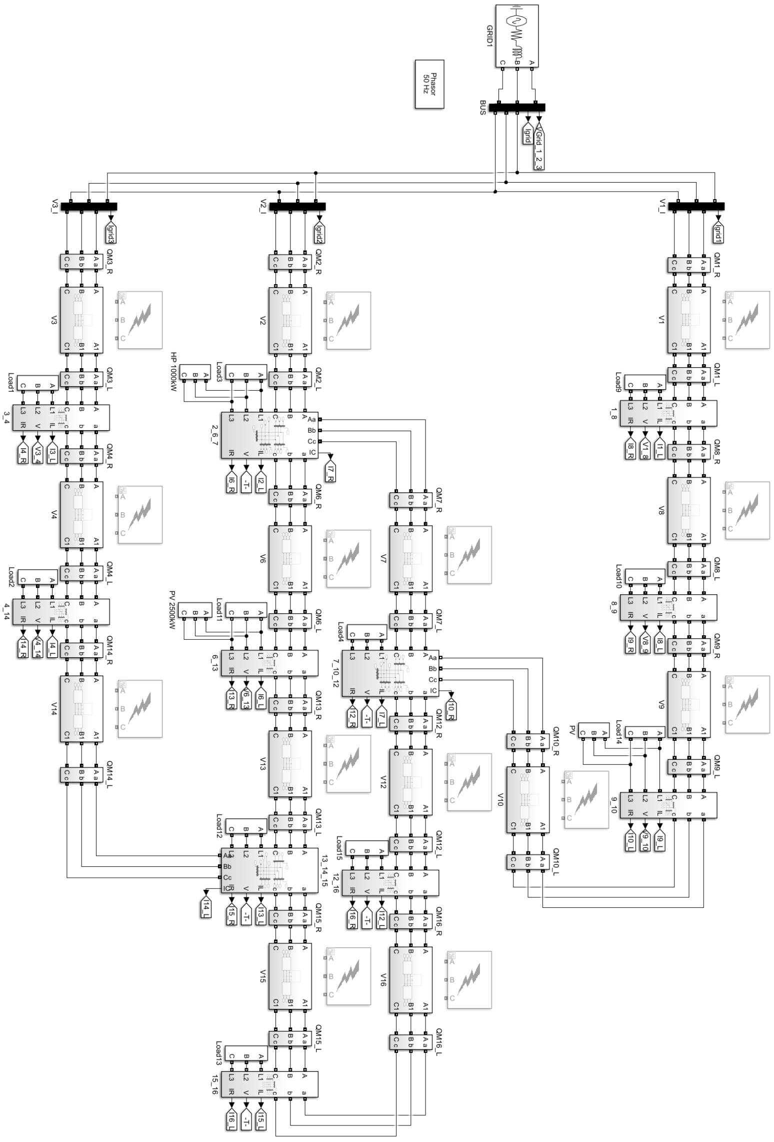

Figure 7

The microgrid topology model in the Simulink program

In electrical station 2_6_7, a hydroelectric power plant (HP) was placed, which will serve as the primary base for the microgrid alongside grid supply. In electrical station 9_10, either a photovoltaic power plant (PV) or a battery energy storage system (BESS) will be located, depending on two different scenarios. Of course, for the applicability of islanded operation of such a microgrid, additional energy sources will be needed, leading to a change in operational ratios. For this reason, we will consider only two types of sources for the worst-case scenario. In this topology, 14 fault locations were determined for each feeder.

# 5 Verification of the Functionality of the System for Real Protective Relays

The simulation results were verified for commonly used protective relays, specifically for the output protective terminals SEL-351A, SEL-751A, ABB REF-615, which are currently prevalent in distribution grids.

## 3.4. Directional Overcurrent Protection Measurements for SEL-351A and SEL-751A

The SEL-751A protective relay was powered directly from the AC network at 230 V, while the SEL-351A relay required an autotransformer to reduce the voltage from 230 V to 120 V. Only one reference voltage value was used for measurement due to limitations in the available CMC 256 Plus device outputs, as shown in Figure 8. To set the desired parameters, the AcSELerator QuickSet software was used, and for mutual communication using the GOOSE protocol, the additional AcSELerator Architect software needed to be installed. Both applications are based on a register-based value input method and provide a reliable and stable software environment. The directional element function was used for functionality testing. In the settings, the pickup current was set to 0.5 A with instantaneous action. Both relays were initially blocked by the directional element function's initial values, one using forward direction and the other using reverse direction. SEL protection evaluates directionality based on three criteria: reactive power, voltage, and current. The instructional manual from SEL had more than thirty pages just describing the operation of the directional protection function for determining direction.

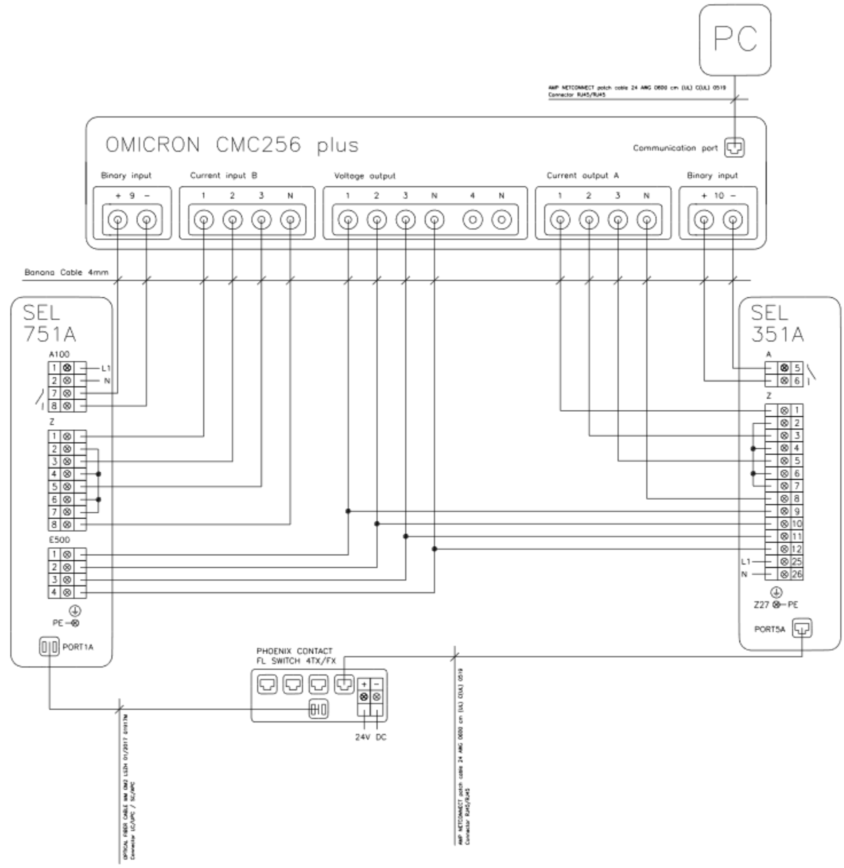

Figure 8

The wiring diagram for directional overcurrent protection measurements with SEL-351A and SEL-751A

## 3.5. Directional Overcurrent Protection Measurement for REF-615

The REF-615 protective relays were powered directly from the AC network at 230 V. Only one reference voltage value was used for measurement due to limitations in the available CMC 256 Plus device outputs, as shown in Figure 9.

The same PCM600 software is used for setting the desired operating parameters and mutual communication via the GOOSE protocol. This application combines register-based value input and block switching of individual modules to set the logic of the protection, but it does not provide the most reliable and stable software environment, as I observed during the configuration.

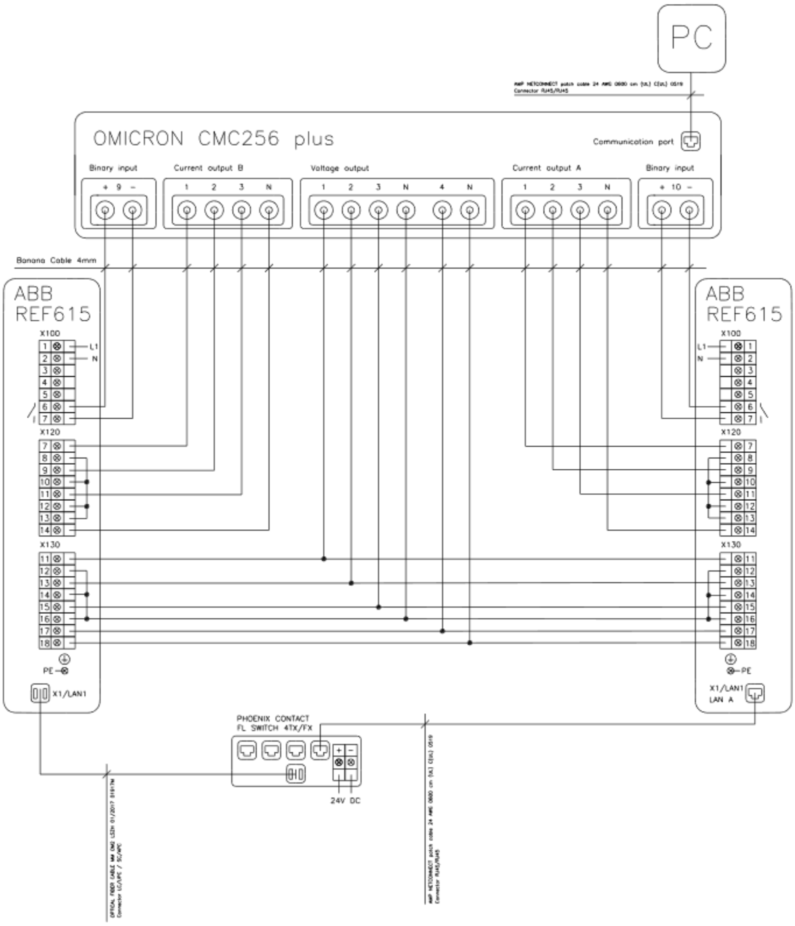

Figure 9

The wiring diagram for measuring directional overcurrent protection with the REF-615 relay

The directional element functions 'DEFHPDEF' and 'DPHHPDOC' were used for functionality testing. In the settings, the pickup current was set to 0.1 A with a time delay of 40 ms. Both relays were initially blocked by the directional element function's initial values, one using forward direction and the other using reverse direction. The REF protection evaluates directionality based on the conventional method of determining direction using voltage and current.

## Conclusions

During measurements and creating a microgrid environment simulation, the assumption of a high demand for designing a new protection system, with the greatest possible utilization of currently deployed protective relays, especially in medium-voltage (MV) distribution networks has been confirmed. This is why it will be necessary to design new devices for the low-voltage (LV) level in the future. These devices will mainly monitor and central data processing with subsequent fault location evaluation using artificial intelligence. These new units will represent simplified versions of current protective relays, featuring only the necessary functions. The fundamental premise is that they will have the capability to measure currents and voltages with the ability to control switching devices for specific sections, whether it's overhead lines or cable lines. However, the issue of central data processing encounters resistance regarding the reliability of such a system. The problem can be partially addressed by using multiple decentralized data managers. Active involvement of consumers in electricity generation, particularly through photovoltaic systems, poses a challenge. Their annual growth and integration into the distribution network will reach a point where the current protection system will become inadequate. This necessitates changes, especially in the distribution network, which will be most affected by these transformations. Current research suggests that both centralized and decentralized systems offer possibilities for implementation in microgrids. When considering a decentralized system, the communication requirements between individual protective relays significantly decrease. Communication occurs only between specific protective relays and involves a smaller volume of data, reducing the need for a robust communication infrastructure. In contrast, a centralized system requires a massive communication infrastructure through which the network or system is managed. Communication among protective relays does not occur directly; it happens only through a central control logic, which evaluates the system's state based on the received measured data. Measuring units continually send the measured data according to the chosen sampling frequency, and the loss of several data packets can significantly disrupt the system, leading to improper evaluations. Real-time control systems are highly sensitive to data loss or delays. The significant development of digital technologies has impacted the progress achieved in control and protection but also highlighted one limitation: the conventional way of thinking. This conventional approach is insufficient for newly installed switched power sources and their proximity to consumption points.

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