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Proceeding Paper

Directional Overcurrent Protection Design for Distribution Network: CIGRE European Medium-Voltage Benchmark Network †

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Abstract: Overcurrent protection is a fundamental aspect of power system protection and is widely utilised in distribution networks. The increasing integration of renewable energy sources (RESs) into the conventional power system has introduced operating challenges due to the variability in fault directions. As a result, protection engineers must not only adjust basic parameters such as pickup current or time delay, but also carefully evaluate the directional protection to align with specific protection objectives and the devices being protected. The complexity of considering multiple aspects in the protection system design can pose challenges for operators in configuring their settings. Therefore, it is necessary to have a systematic approach for protection system design. For this purpose, this paper proposes a methodology for protection system design focusing on directional overcurrent protection setting configuration with detailed implementation. A well-known distribution network, the CIGRE European (EU) medium-voltage (MV) benchmark network, is used to test and validate the proposed methodology with the support of DIgSILENT PowerFactory version 2023 SP1. This article provides a useful document for the configuration of overcurrent protection systems in order to prepare for the challenges arising from the high integration of RESs in the future grid.

Keywords: CIGRE EU MV network; distribution network; directional; overcurrent protection; RES; testing; validation

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1. Introduction

The transition toward clean energies has led to the widespread integration of renewable energy sources (RESs) in many sectors, particularly power systems [1]. This transformation offers substantial advantages across economic [2], technological [3], and environmental [4] domains. Nevertheless, alongside these benefits, the power system is facing many challenges in management and operation due to the inherent uncertainty and intermittency of power generation from RESs [5]. RESs such as wind and solar are dependent on weather conditions, leading to fluctuating power generation. This variability complicates the task of protection coordination, where devices like relays, circuit breakers, and fuses must distinguish between normal operational changes and fault conditions [6]. In addition, RESs contribute another source of fault current to the network, potentially increasing the total fault level while changing the magnitude and direction of fault currents [7]. Indeed, many RESs, especially those connected via power electronics, have different fault current characteristics. They can rapidly change the magnitude of their fault contribution and, in some cases, even reverse the direction of fault current flow [8]. Therefore, this requires the protection system to be adapted to this transformation.

In recent years, there has been much research on RES penetration influencing the protection system [9,10]. The literature review in this field can be subdivided into two main categories. The first category delves into the short circuit analysis under the influences of RES penetration within the system. Accordingly, the authors in [11] investigated the transient response of short circuit current fed from non-synchronous generators. The short circuit currents in the high integration of RESs witnessed a significant change in magnitude and direction compared to the observed in conventional power systems without integration. Similarly, the authors in [12] believe that the increase in short circuit level can burden the protection system and require solutions to address this issue. Based on that, some groups of researchers are focusing their research on the second category, protection system configuration according to the short circuit characteristic. Research on this category can be highlighted at [13,14]. In [15], the combination of circuit breakers and protection relays is proposed for the CIGRE MV EU benchmark distribution network. Similarly, in paper [16], in the context of overcurrent protection, the authors defined the relay settings based on power system protection theory. However, the validation of the proposed protection system design is still missing. To address the lack of protection relay testing before actual implementation, there are some proposed testing methods such as real-time simulation [17] and hardware-in-the-loop [18]. The relevant devices and hardware are emphasised in these methods. The presented literature shows a lack of general overview of protection system configuration settings. Therefore, it is essential to have a systematic approach to configure protection systems in a future-extendable manner in the scenario of more RES integration.

To meet this need for a comprehensive protection system design, this paper presents a methodology for configuring a protection system that adapts to rapid changes in the future power system. Accordingly, an overcurrent protection system, which is one of the most popular features in power system protection, is implemented in this paper. The design of overcurrent protection is executed for a well-known test system, the CIGRE MV EU benchmark distribution system, under different operating conditions. With the support of DIgSILENT PowerFactory, the short circuit is analysed and used to configure the overcurrent protection. The proposed protection system is validated with the relay model inside the software.

The remainder of the article is divided into the following sections. Section 2 provides an overview of overcurrent protection with two features, non-directional and directional. Section 3 gives the methodology of protection system configuration in step-by-step implementation. Section 4 gives the case study with the test system description, the design of overcurrent protection, and its configuration. The validation of the proposed protection system is also given in this section. Finally, Section 5 concludes this paper with a summary and suggestions for further studies.

2. Overcurrent Protection

Overcurrent protection is one of the most popular features of protection systems in distribution networks. The overcurrent protection relay works on a very basic principle; it generates and sends the trip signal to the circuit breaker (BK) by comparing the current flowing through the secondary winding of the current transformer (CT) with a predetermined threshold (pickup current). The overcurrent protection relay can be divided into two categories: (a) non-directional and (b) directional.

2.1. Non-Directional Overcurrent Protection

Non-directional overcurrent protection relays are applied widely in radial distribution feeders, the most common worldwide type of distribution system. In addition to comparing current flowing through it with preset thresholds, it also stands out with the ability of operating time coordination by time versus current magnitude characteristic curves (*I*-*t*).

Let us take an example of its time-operating coordination. A system with one source and parallel transmission line with two protection relays located at both ends is illustrated in Figure 1a,b. In case of a fault occurring in the middle of Line A, as shown in Figure 1a, relays R1 and R2 must be tripped before relays R3 and R4 to ensure a continuous system (Line B is still in service). This can be achieved by setting the operating time of relays R1 and R2 faster than relays R3 and R4. Similarly, as shown in Figure 1b, in case of a fault occurring at bus 2, relays R1 and R2 must be tripped primarily, while relays R3 and R4 in this case are backup protection.

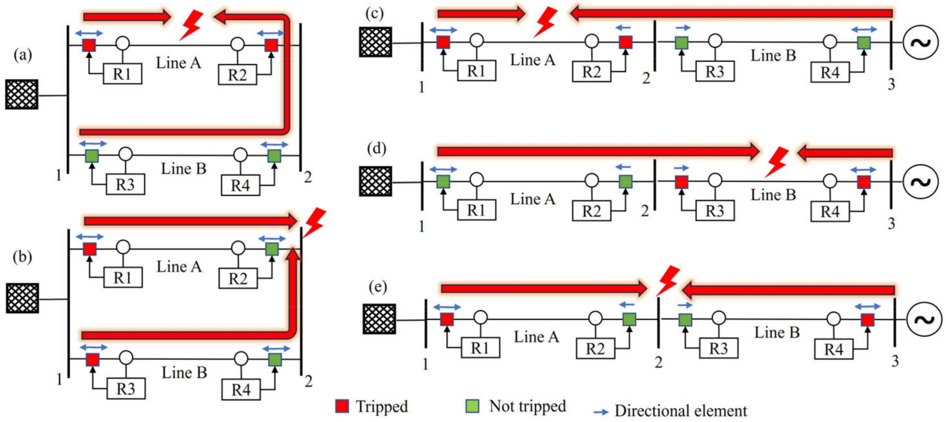

Figure 1. Typical applications of overcurrent protection relays in transmission system. (**a**,**b**). A system with one source and parallel transmission line. (**c**–**e**). Double-end-fed radial system.

Therefore, depending on the protection purposes and fault scenarios, the operating time of overcurrent protection can be coordinated. The time coordination can become simple with three current-time characteristics: (i) instantaneous (ANSI 50), (ii) time-dependent, defined time and inverse time (ANSI 51), (iii) combination of instantaneous and time-dependent. The operating time according to inverse-time characteristics can be defined as:

$$t_{trip} = TMS \frac{a}{PSM^b - c} \quad (1)$$

$$PSM = \frac{I_r}{PS} \quad (2)$$

In Equations (1) and (2), *TMS* is the time-multiplier setting of the relay, *PSM* is the plug-setting multiplier, *PS* is the plug setting of the relay, I_r is the pickup current, and the parameters of characteristic curves a, b, and c follow IEC 60255 [19] and IEEE C37.112 [20].

2.2. Directional Overcurrent Protection

The directional overcurrent protection relay is essentially non-directional overcurrent with the additional feature of a preset direction of protection (forward or reverse), as shown in Figure 2.

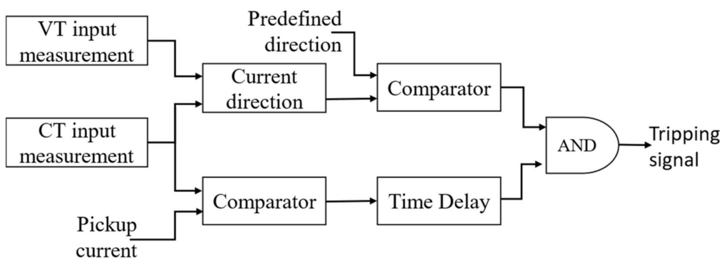

Figure 2. Block diagram of directional overcurrent protection.

The directional overcurrent protection relay is widely used on the transmission side in distribution networks. Taking its application illustrated in Figure 1c–e, a double-end-fed radial system is used, with two relays located at both ends of the transmission line. In case of a fault occurring in the middle of Line A, as shown in Figure 1c, the fault current flows in both directions, from source at bus 1 and from source at bus 3. Relay R1 is a non-directional overcurrent relay; therefore, it operates in this case without considering the current direction. In contrast, relay R2 is a forward directional overcurrent relay, which can 'see' the current flowing in front of it (from the source at bus 1 to relay R2). In this case, relay R2 can operate because the current direction is the same as its preset direction. Similarly, in Figure 1d, relays R3 and R4 can 'see' the fault current. However, in case of a fault occurring at bus 2, as shown in Figure 1e, relays R2 and R3 do not operate since their preset directions are not matched with the fault current direction. Therefore, setting the direction for directional overcurrent protections in different fault scenarios is extremely important.

The directional decision of the relay can be made using the relay characteristic angle (RCA). RCA is the angle referred to as the maximum torque angle (MTA) with polarising voltage as shown in Figure 3. It defines the operating sectors of the relay, and the forward and reverse zones. By evaluating the phase angle between the operating current and the polarising voltage, the relay determines whether it falls within the predetermined forward or reverse region specified by RCA, thereby enabling or disabling fault directional trip. Additionally, the flexible directional relay is designed to guarantee the right working zone and prevent relay mis-operations. It allows the phase angle operating region to be stretched or retracted through its minimum/maximum forward and reverse angle settings. In certain popular networks, the minimum/maximum forward and reverse angles of the protection system are set to ±86 degrees and ±94 degrees, respectively, while RCA is commonly set to 90 degrees.

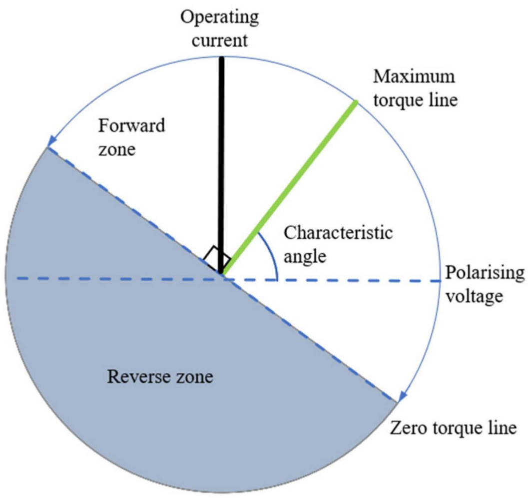

Figure 3. Directional overcurrent relay operating characteristics.

3. Protection System Design Methodology

Figure 4 shows the methodology for protection device setting configuration. The authors believe that this methodology can be applied in every type of protection system, such as fuse, overcurrent protection relay, and distance protection relay. To obtain the effective protection device configuration, these steps must be followed:

- **Identification of protection devices**: During this phase, the selection of protection devices, such as fuses, circuit breakers, and protection relays, is determined according to voltage level, current rating, specific standards, or system requirements. Some standards outline specific requirements for protection devices corresponding to each voltage level within power systems. For example, at low-voltage levels, IEC 60947-2 requires the use of circuit breakers for a maximum operational voltage of 1 kV AC or 1.5 kV DC [21]. In medium-voltage applications, standards such as IEC 60255 provide requirements for protective relays designed for voltage levels ranging from 1 kV to 36 kV [22].

- **Definition of protection zones**: The selection of protection region, which is isolated by protection devices in case of fault, is established in this phase. This involves identifying distinct areas of the power system that require protection, such as feeders, buses, transformers, and generators. Once the regions are selected, clear boundaries for each protection zone must be established, corresponding to the protective devices selected in the initial step. The possibility of overlap between protection devices is also considered in this phase.
- **System analysis**: The analysis is a comprehensive analysis of the power system to understand potential fault scenarios and normal operating conditions. This analysis examines various fault types that could occur, including three-phase faults, single-line-to-ground faults, and line-to-line faults. During this phase, it is essential to assess the operational scenarios in which these faults might arise, taking into consideration variations in load and generation, or network topologies. Additionally, normal operating currents are evaluated to establish baseline conditions. This analysis provides critical data necessary for setting the protection parameters, ensuring that devices can effectively detect and respond to abnormal conditions while remaining operational during normal operational scenarios.
- **CT (current transformer) and VT (voltage transformer) ratio selection**: The selection of CT and VT ratios is performed based on the findings from the analysis in the second step. The appropriate CT ratio is determined by the maximum expected load current and potential fault currents in the system. It is crucial to select a ratio that allows CT to accurately reproduce current signals without saturation during fault conditions, ensuring reliable protection device operation. Similarly, the VT ratio is chosen based on the system voltage levels to ensure that the voltage measurements accurately reflect the operating conditions.
- **Threshold configurations**: Threshold configurations involve establishing precise threshold values for the protection devices to ensure that they detect and respond to abnormal conditions accurately. Each protection device, such as relays and circuit breakers, has specific operational thresholds for parameters like overcurrent, undercurrent, and voltage levels. During this phase, these threshold values are defined based on the results of the system analysis and normal operating conditions. For example, overcurrent thresholds should be set above the maximum load current but below the expected fault current to ensure the timely detection of faults while preventing nuisance tripping during normal fluctuations.
- **Time setting configurations**: This step entails defining specific time delays for the operation of protection devices, ensuring timely and effective responses to fault conditions. In this phase, protection engineers establish coordination settings to ensure that devices operate in a sequential manner, allowing only the nearest device to a fault to trip first. The time settings are determined based on the characteristics of the protection devices, the type of fault, and the specific protection zone layout. Additionally, engineers consider the selectivity of the protection system during this phase, ensuring that devices are coordinated properly across different zones.
- **Other configurations**: Other necessary parameters, such as directional elements and zone interlocking, are defined to complete the protection setting configuration. Additionally, configurations may include settings for features of protection devices such as harmonic filtering, under-voltage protection, and frequency protection, ensuring comprehensive coverage for various fault scenarios.
- **Protection system validation**: The design of the protection system must be validated before actual implementation. The protection system needs to meet the criteria and standards to ensure that it provides adequate protection for the power system under various faults and operating conditions. Offline simulation, real-time simulation, and hardware-in-the-loop are popular methods that can be used to test the protection configuration.

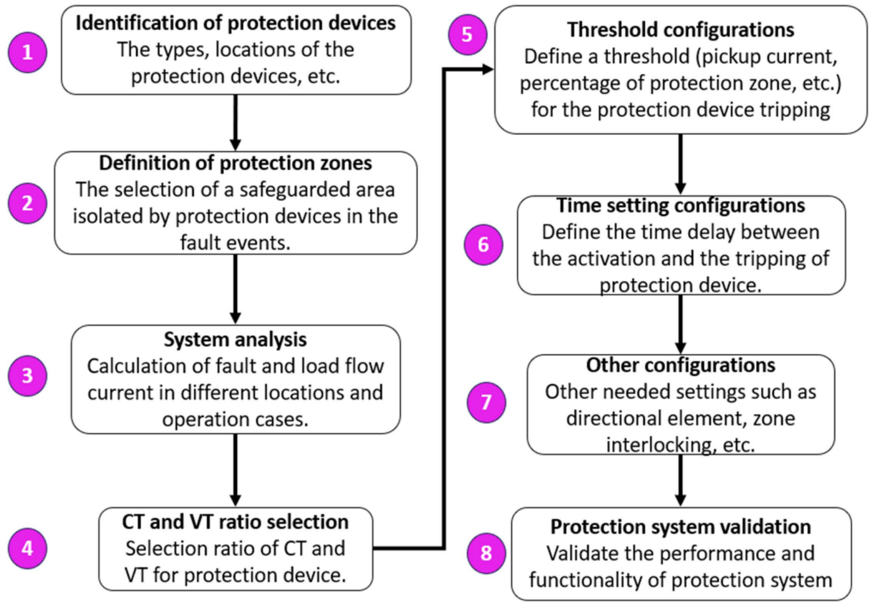

Figure 4. Methodology of protection system design.

4. Case Study

4.1. Test System

In this paper, the CIGRE EU MV benchmark network is used as the test system for the overcurrent protection system design. This benchmark system is a scaled-down representation of a medium-voltage network in southern Germany and is designed to reflect the 50 Hz power system commonly used across European countries. This test system is recommended by CIGRE for studying behaviours of power systems due to the high integration of RESs [23].

This network consists of 14 nodes with a nominal based voltage of 20 kV and connects 18 loads, which are divided into residential, commercial, and industrial types. The benchmark has two feeders. The network topology can be configured through these feeders by using the three isolation switches (S1, S2, and S3). More detailed information on this test system is available in [23]. Further variety may be introduced through eight operating cases of means of configuration switches S1, S2, and S3 as shown in Table 1. If these switches are open, then both feeders are radial. Closing S2 and S3 in feeder 1 would create a loop or mesh. With the given location of S1, it can either be assumed that both feeders are fed by the same substation or by different substations, and closing S1 interconnects the two feeders through a distribution line.

Table 1. Operating cases with switch states. 0: Open; 1: Closed.

Case	S1	S2	S3	Case	S1	S2	S3
1	0	0	0	5	1	0	0
2	0	0	1	6	1	0	1
3	0	1	0	7	1	1	0
4	0	1	1	8	1	1	1

4.2. Overcurrent Protection System Design

Following the methodology detailed in Section 3, the subsequent steps for protection system design in the test system are executed as follows:

- **Identification of protection devices**: In this case study, the overcurrent protection system is used, including both non-directional (at the beginning of the transmission line) and directional overcurrent protection relays (at the end of the transmission line) in conjunction with circuit breakers to meet the MV requirements. The arrangement of relays and circuit breakers is located at both ends of transmission lines, as illustrated in Figure 5.

- **Definition of protection zones**: Protection zones are selected to cover the entirety of the transmission line. In this setup, the primary protection is assigned to the relay positioned at the end of the transmission line (protection relay Bx), while the backup protection is assigned to the relay situated at the beginning of the transmission line (protection relay Ax).
- **System analysis**: The short circuit analysis is illustrated in Figure 6. The two types of short circuit which are used in this analysis are a three-phase short circuit and a single-line-to-ground short circuit. Both cases are executed in maximum short circuit calculations. As shown in Figure 6, the magnitude of the short circuit current varies due to different operating conditions of the test system. Notably, case 8, where all three switches are closed, exhibits the highest short circuit current values for both the three-phase and single-line-to-ground cases. This is due to the interconnected topology, where the short circuit current is the sum values of the currents from the two feeders. However, the phase angle of the short circuit current does not exhibit substantial variation. Additionally, normal operating current levels were evaluated during this phase, revealing significant variations resulting from the different network topologies.
- **CT and VT ratio selection**: The calculation of the primary value of CT is based on the largest operating current across all the operational scenarios involving switches. To ensure the reliability of the relays, the CT ratio is considered with the overload situation as including more than 25%, or, in other words, it is equal to 125% of the largest operating current magnitude. The primary value of VT is selected based on the normal-based voltage of the system. The secondary values of CT and VT are selected as 1 A and 5 V, respectively.
- **Threshold configurations**: The overcurrent protection uses a combination of inverse-time and instantaneous features. Following [16], as shown in Table 2, for inverse-time features, the pickup current is selected as 2.0 to 3.0 times the maximum operating current, while for instantaneous features, the pickup current for the primary protection is set at 1.5 times the rated thermal current of the feeder line, while the pickup current for the backup protection is established as 1.5 times the minimum three-phase short circuit current.
- **Time setting configurations**: Regarding the inverse-time characteristic, the ANSI extremely inverse curve is used for the entire overcurrent protection relay with TMS as 0.05. The delay time of the instantaneous feature is selected as 300 milliseconds and 50 milliseconds corresponding to backup and primary protection.
- **Other configurations**: In this case study, protection relay Ax is of the non-directional type. On the other hand, the directional element is configured for relay Bx to operate in the forward direction, enabling the protection devices to effectively "see" and safeguard the area directly in front of them. Accordingly, MTA in the setting of the directional overcurrent relay in the network is set to 90 degrees.
- **Protection system validation**: For validation, the authors in this paper use offline simulation in DIgSILENT PowerFactory 2023 SP1 software. The model of real-world relay REF 630 from the ABB company is selected to test the relay configuration. The validation study is implemented in case 8, interconnected topology. In this case, as shown in Figure 7a, in the scenario of a three-phase short circuit occurring in the middle of Line 1–2, both relays can enable the trip signal. In contrast, in the case of a three-phase short circuit occurring at bus 2, relay B2 with a forward direction setting fails to operate the trip signal, as shown in Figure 7b.

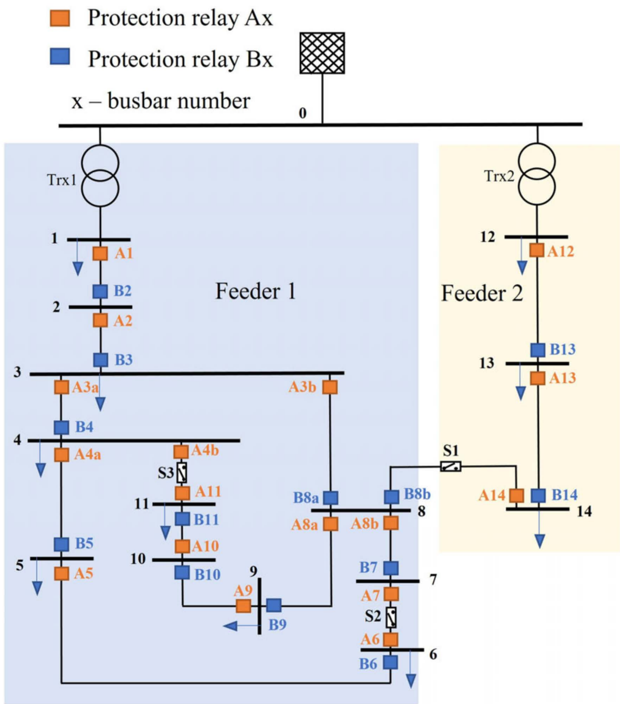

Figure 5. Protection relay location in the test system.

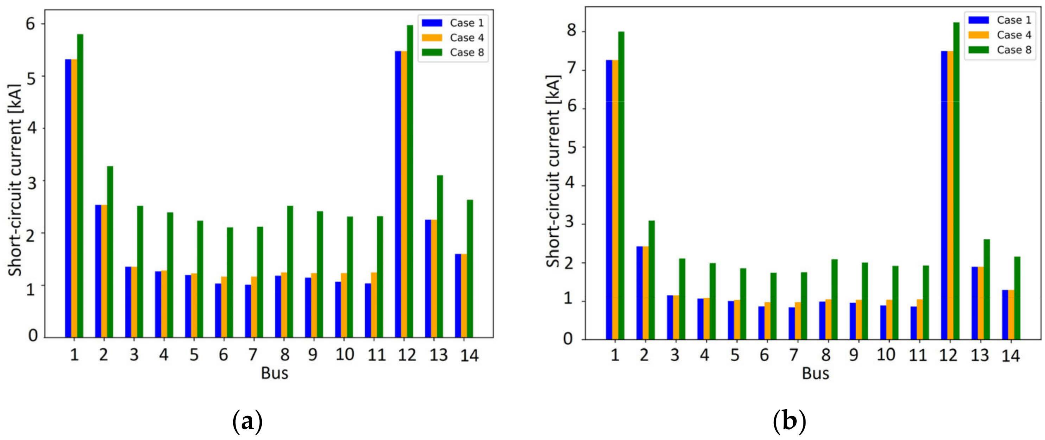

Figure 6. Short circuit current magnitude obtained at buses. (**a**) Three-phase short circuit, and (**b**) single-line-to-ground short circuit.

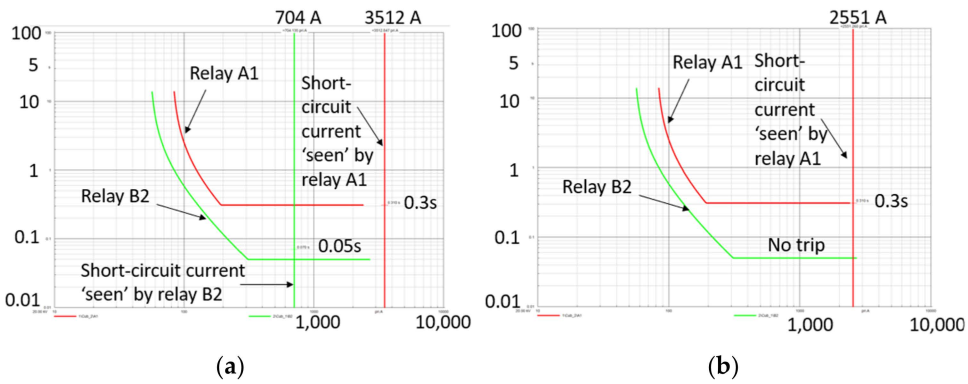

Figure 7. Relay A1 and B2 characteristic. (**a**) Short circuit occurs in the middle of Line 1–2, and (**b**) short circuit occurs at bus 2.

Table 2. Protection relay configuration.

Relay	CT Ratio	Ioc [A]	ANSI 51	ANSI 50		Relay	CT Ratio	Ioc [A]	ANSI 51	ANSI 50	
			Ir [kA]	Ir [kA]	Delay (ms)				Ir [kA]	Ir [kA]	Delay (ms)
A1	200:1	170	0.40	3.80	300	A3b	100:1	84	0.19	1.77	300
B2	200:1	169	0.27	2.94	50	B8	100:1	85	0.13	1.06	50
A2	200:1	169	0.40	3.63	300	A8a	50:1	59	0.14	1.72	300
B3	200:1	170	0.27	2.26	50	B9	75:1	59	0.08	1.02	50
A3a	75:1	69	0.16	1.89	300	A9	50:1	34	0.08	1.59	300
B4	75:1	69	0.11	1.21	50	B10	50:1	34	0.05	0.95	50
A4a	50:1	49	0.12	1.78	300	A10	50:1	13	0.03	1.54	300
B5	50:1	49	0.08	1.13	50	B11	50:1	13	0.02	0.92	50
A5	50:1	21	0.05	1.54	300	A12	100:1	84	0.19	3.37	300
B6	50:1	21	0.03	1.07	50	B13	100:1	84	0.13	2.02	50
A8b	75:1	23	0.05	1.51	300	A13	100:1	83	0.19	2.14	300
B7	50:1	20	0.03	0.92	50	B14	100:1	83	0.13	1.43	50

5. Conclusions

The widespread integration of RES into power systems offers numerous benefits; however, it also presents operational challenges; for example, it impacts on power system protection. Indeed, RESs contribute to increased short circuit magnitude values and alter the direction of current flow, necessitating a systematic approach to power system protection design to mitigate these impacts. This paper introduces a methodology to address this need. Accordingly, the design of an overcurrent protection system that incorporates both directional and non-directional features is implemented in a well-known test system, the CIGRE EU MV distribution network.

This paper can be regarded as a valuable resource for protection engineers who are seeking an aid document in preparation for further RES integration in the future. The presented methodology in this paper employs software-based validation methods and theoretical calculations for protection system design. Therefore, specialised analysis tools and advanced validation methods, such as real-time simulations and hardware-in-the-loop testing, can be utilised for further research. Moreover, leveraging this methodology in a larger test system can significantly advance wide-area monitoring, control, and protection capabilities in future power systems.

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