Concise Definition of the Overcurrent Protection System for CIGRE European Medium Voltage Benchmark Network

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***Abstract*—In the significant widespread transition towards clean energies, there has been an unstoppable trend in integrating renewable energy sources (RESs) in distribution networks. However, the massive penetration of integrated multi-sources into conventional distribution systems may create several operational problems, such as malfunctioning protection systems. This paper concisely defines the setting for overcurrent protection applied to the CIGRE European (EU) Medium Voltage (MV) benchmark network. The benchmark system is commonly recommended for RESs penetration studies. In this paper, the authors show the calculations and results of the non-directional and directional overcurrent protection relay in a very educational and detailed way. The definition of the settings considers several operating situations and two short-circuit (SC) types: three-phase and single-line-to-ground. The main contribution of this paper is a well-documented and validated overcurrent protection settings of the CIGRE EU MV that can be used for teaching and research purposes.**

Keywords— CIGRE MV benchmark, distribution networks, overcurrent protection, protection systems.

I. Introduction

Renewable energy sources (RESs) are considered potential energy sources and gradually replace conventional energy sources, promoting the service on increasing energy demand worldwide [1]. Consequently, the rise of integration of RESs into electric power distribution networks brought numerous positive impacts in the economic, technological, environmental and other sectors [2]. Along with benefits, their higher integration poses significant effects and challenges in the planning system and operation networks according to the uncertainty and inherent intermittence of power generation from renewable energy sources [2]. Indeed, the integration of RESs changes the network topologies and leads to different intermittent fault levels [3] [4]. These changes are a protection challenge for pre-set protection systems, as failure to operate when needed may occur. Hence, to reliably operate and control power systems integrated with RESs, there is a crucial need to design new protection methods or modify the existing protection schemes.

Protection plays a crucial role in the operation and control of the power system. A fault in the power system can affect normal operation and trigger cascading consequences if not rectified in time. Therefore, one of the major steps in fault clearing and system restoration is to locate the accurate fault as early as possible. Therefore, identifying and isolating faults in an electrical power system is one of the most essential and critical tasks undertaken by protection engineers. Early detection and location of faults lead to faster system restoration, improved system reliability, reduced operating costs and losses, easier task for maintenance personnel, and improved consumer satisfaction.

In the recent past, much research has been done on the protection of electrical power grids integrated with RESs [5]–[7]. The authors in [8] proposed the development of an overcurrent protection scheme due to the change of upstream of overcurrent protective devices in variations of short-circuit currents on the IEEE Distribution 13-Bus Test Feeder System. In [9], a communication-based protection scheme implementing directional overcurrent protection relays instead of reclosers at the line, assisted by inter-tripping and blocking transfer functions, is proposed. The protection strategy guarantees selectivity regardless of whether the generating units are connecting to the network or not and can be designed to retain either the fuse-blowing or fuse-saving philosophy. In [10], the authors considered the impact of integrating RESs into power system protection on overcurrent time delay settings. The proposed optimisation method using genetic algorithm optimisation from this paper can be used to evaluate the impact of integrating RES on the existing overcurrent settings and can provide new settings without the need to replace the protection devices.

Similarly, the concept of designing a protection system for an electrical power system integrated with RESs was introduced by [11] based on the combination of circuit breaker and protection relay for the CIGRE Task Force C06.04.02 Medium Voltage (MV) benchmark distribution network extensively used for the studies on RESs penetration. However, the authors in [11] proposed a protection system including only one main and two backup protection relays with the purpose of protecting the main elements, such as the transformer, under the passive network behaviour. The configuration of the protection system is also introduced in this paper with an actual unknown load which can interfere with the adequate performance of the protection system.

To fill this gap, this paper is to take proper overcurrent protection aiming to protect full elements in the network under RESs integration. With the support of DIgSILENT PowerFactory – one of the leading power system analysis software, the benchmark network is analysed under entire operating cases and two levels of two common SC types, three-phase and single-line-to-ground. Based on this analysis, the problem definition of the protection system is given, and then the overcurrent protection relays are located with their configuration settings.

The following sections make up the remainder of the paper. Section II overviews overcurrent protection with two features, non-directional and directional. Section III describes the network with the analysis of nominal operating cases and short-circuits situations. Section IV provides the protection system with the protection relays' location and configuration settings. Finally, the last section concludes the paper with a summary of the workload and main contribution.

II. Overcurrent Protection Relay

An excellent electrical power system needs to have reliability and security that can be achieved through the protection system. A protection relay is the "brain" of a protection system that can detect abnormal conditions in the power system and automatically operate to isolate the faulty from the rest of the system as quickly as possible [12]. Overcurrent protection is one of the most common functions of a protection relay that is used in distribution networks. The operating principle of the overcurrent protection relay is extremely simple; it compares the current through the secondary winding of the current transformer (CT) with a predetermined threshold (pickup current), then generates and sends the trip signal to the tripping circuit of the circuit breaker (BK) to isolate the faulty. The overcurrent protection relays applied in the power system could be directional (operating in a predetermined direction) and non-directional (operating regardless of current direction), depending upon the topology of the distribution system [13].

A. Non-directional feature

Non-directional overcurrent protection relays are mainly used for radial distribution feeders, the most common type of worldwide distribution system. Regarding the operating characteristics of this type of overcurrent protection relay, the operating time is defined by a time versus current magnitude curve (I-t). There are three main types based on current-time characteristics: (i) Instantaneous; (ii) Time-dependent with two categories, defined time and inverse-time; and (iii) Mixed, the combination of the previously stated. While the instantaneous type is known as "high speed" operation with no time delay intentionally, the time-dependent type allows protection engineers to have flexible use of two categories, defined time and inverse time. Define time protection relays operate with some intentional time delay and can be adjusted along with the current pickup level. Inverse-time protection relays have operating time depending on the magnitude of the current, generally with an inverse curve characteristic.

When referring to overcurrent protection functions, according to ANSI/IEEE C37.2 [14], the ANSI device number is 50 for an instantaneous overcurrent and defines-time overcurrent. In contrast, the inverse-time overcurrent function is denoted by ANSI device number 51. The trip time of ANSI 51 protection relay can be defined as:

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

$$PSM = \frac{I_r}{PS} \tag{2}$$

where *TMS* is time-multiplier setting of the relay, *PSM* is plug-setting multiplier, *PS* is plug setting of the relay, I_r is the pickup current and parameters of relay characteristics, a, b, and c. These parameters are based on the inverse curves according to IEC 60255 [15] and IEEE C37.112-1996 [14].

B. Directional Overcurrent feature

Currently, according to modern networks, with the integration of more than one source and multiple transmission lines leading to different current directions, there has an increasing combination of non-directional and directional overcurrent protection relays. A directional overcurrent relay uses the same principle as an overcurrent relay. However, in this feature, the directional relay operates when the current exceeds a predetermined current direction. In other words, the directional overcurrent relay or ANSI 67 [14] is the combination of non-directional overcurrent relay features (ANSI 50 and ANSI 51) and a direction unit.

According to [16], the directional protection relay makes its directional decision by determining if the angle between the operating current (I_0) and polarising voltage or reference voltage (V_{ref}) has entered the elements operating sector, where the *relay characteristic angle* (RCA) setting is used. A 360° setting range is used to adjust the directional element operation. RCA is the impedance angle commonly referred to as the *maximum torque angle* (MTA). By convention, it is the complex conjugate of the operating current phasor (at maximum torque) with respect to the polarising voltage (reference). To ensure the correct operating zone as well as prevent misoperation of the relay, the flexible directional relay design is introduced that allows the phase angle operating area to be extended or retracted through its minimum/maximum forward and reverse angle settings. The minimum forward angle setting adjusts the clockwise sector relative to the RCA, and the maximum forward angle, the counter-clockwise sector. Likewise, the reverse operating area is controlled using the minimum/maximum reverse angle settings. The minimum reverse angle setting adjusts the clockwise sector relative to RCA, and the maximum reverse angle or the counter-clockwise sector. In some standard networks, RCA is typically set to -90° with minimum/maximum forward and reverse angle of the protection system set as +/- 86° and +/- 94° [16], respectively, as shown in Fig. 1.

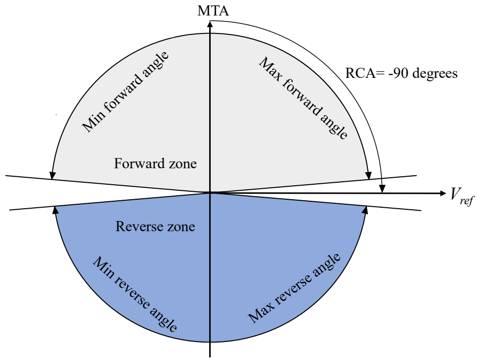

Fig. 1. Phase angle characteristic in the V-I plane.

III. Network Description

This MV benchmark system is created for typical network integration of renewable and distributed energy resources in Europe, which is the reduced version of an MV network in southern Germany. This benchmark network represents the typical European MV distribution, and it is composed of 14 nodes with a nominal base voltage of 20kV, where residential, industrial and commercial loads are connected. The MV distribution network benchmark consists of two feeders with a system frequency of 50 Hz. Feeder 1 uses overhead lines, while underground cables are used in the entire system of Feeder 2. Three isolation switches (S1, S2 and S3) allow reconfiguring the network topology. All the network details are included in [17]. Other variety may be introduced through operating cases of configuration switches S1, S2 and S3. 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 be assumed that both feeders are fed by the same substation or different substations. Closing S1 interconnects the two feeders through the distribution line. According to the three states of isolation switches, there are eight operation cases of the benchmark network system; Case 1 (all switches are opened), Case 2 (S3 is closed), Case 3 (S2 is closed), Case 4 (S2, S3 are closed), Case 5 (S1 is closed), Case 6 (S1, S3 are closed), Case 7 (S1, S2 are closed), and Case 8 (all switches are closed). The benchmark system's nominal operating cases and short-circuit events are analysed using DIgSILENT PowerFactory 2022 SP1.

A. *Nominal operating analysis*

The nominal operating of the benchmark network in eight cases is considered based on the state change of configuration switches, S1, S2 and S3, which means changing the network type from loop to mesh and interconnect. As shown in Table I with the nominal voltage at bus 2, the change in the state of the switches shows no marked difference in the voltages at buses in magnitude and phase angle. In terms of operating current in the benchmark network, the radial and mesh networks corresponding respectively to the switching state of S2 and S3, do not make a significant change in operating current magnitude and phase angle. However, the switching state of S1 or the interconnect between two feeders leads to a marked difference in magnitude and phase angle.

B. *Short-circuit analysis*

For different operating cases of the system based on the states of the switches, the magnitude of SC currents needs to be considered. There are two types of SC made on this system as three-phase and single-line-to-ground in two different levels, maximum and minimum. The relevant SC currents are given as settings for SC calculation at the external grid that can be given in Table III.

TABLE III. Settings of short-circuit calculation.

	Maximum short-circuit current	*Minimum short-circuit current*
Short-circuit power *R/X* ratio	5000 MVA 0.1	3000 MVA 0.15

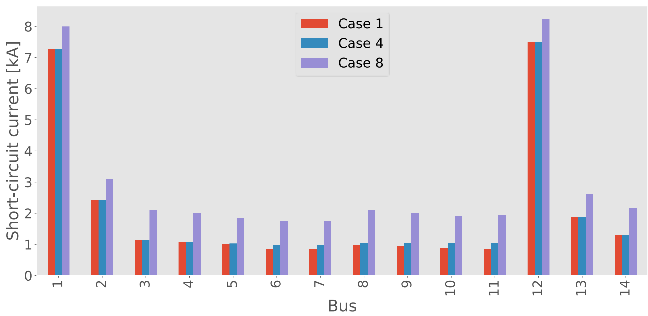

Fig. 2. Magnitude of single-line-to-ground SC current at maximum SC level.

In two types of SC occurring at buses in two different levels, the magnitude of SC currents increases gradually from Case 1 to Case 8; with the minimum values at Case 1, the radial topology; and the maximum values at Case 8, the interconnect topology. In addition, the single-line-to-ground SC has larger magnitude values than the three-phase SC in two levels of SC. Accordingly, in both levels and situations of short-circuit cases, the SC current angle shows no significance, considering the SC current flows through the transmission line.

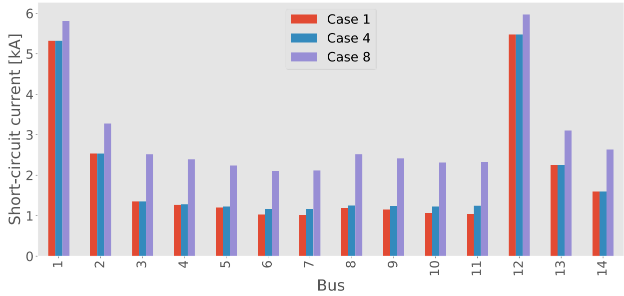

Fig. 3. Magnitude of three-phase SC current at minimum SC level.

IV. Overcurrent Protection System

The objective of the protection system is simply to require such overcurrent protections to isolate short-circuit faults; however, with the change of angle in nominal operating current due to the states of S1, the overcurrent protection is required to detect the right direction of current and not give the false trip when the network topologies change. In addition, the magnitude of current in SC cases showing Case 1 with minimum values and Case 8 with maximum values, these cases are taken into consideration for the protection system design of the benchmark network.

A. Location of protection relay

In an MV distribution grid or benchmark network, there are usually two levels of protection: the main feeder protection at the beginning of a feeder and the secondary protection at the transformer level, which is used to protect the transformer against abnormal conditions such as overloading or short-circuit, and provides backup protection to the feeder protection device [18].

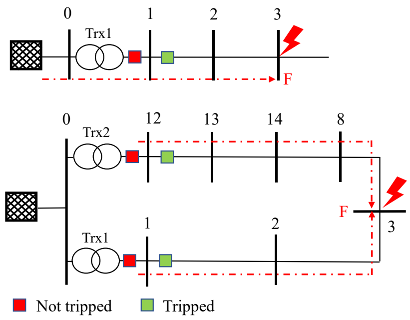

Fig. 4. Tripped and not tripped relay when the fault occurred at bus 3.

The coordinated operation of both protection relays is essential to maintain the selectivity of the protection system. However, to ensure the continuity of operation of the rest of the network under the fault, it is necessary to distribute more protection relays, which the previous paper lacked [11] [18]—taking the main feeder protection into account. The fault occurs at bus 3, as shown in Fig. 4; the protection relay at the beginning of the feeder is the main protection, which sends the trip signal first when the fault occurs, and then the protection relay at the secondary side of the transformer is the backup protection. In the case of the radial topology of the benchmark system (S1 is opened), the trip signal from the protection relay gives the disconnected of the load at bus 2, which is otherwise operable. Furthermore, in the case of the loop topology (S1 is closed), the trip signal sheds all the loads at entire buses in the benchmark system. In reality, the protection system is usually distributed at both ends of the transmission line to prevent faults from occurring on the transmission line, increase the system reliability, and maintain the loads. Therefore, the MV system protection is fully designed through circuit breaker combined with directional overcurrent protection relays which are located as Fig. 5. Relay named Ax and Bx where x is the sequence number of protection relay based on the bus number with the responsibility for protecting the network elements in case of fault occurring on buses or transmission lines.

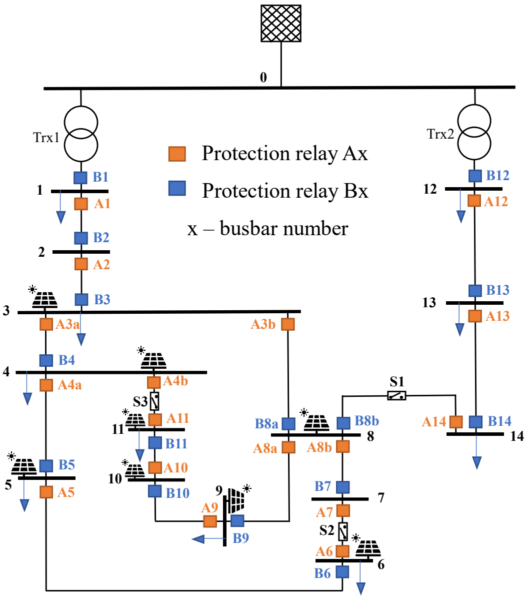

Fig. 5. Location of overcurrent protection relay in benchmark network.

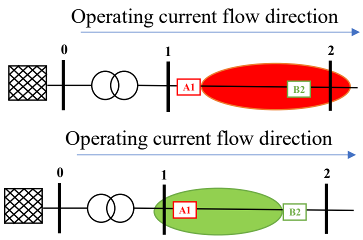

Fig. 6. Forward direction “seen” by protection relay.

For the purpose of protecting the front elements, the protection zone of relays Ax and Bx is shown in Fig. 6, where these relays must be set up so that the forward direction can be “seen”.

B. *Protection relay configuration*

a) Defining CT ratio: To define the value of CT ratio for each relay in the protection system, the magnitude of nominal load flow current sensed by the relay should be considered. For the entire operating cases of switches, the magnitude of nominal load flow current, in which case is larger will be selected for the CT ratio calculation. In addition, to ensure the reliability of the relays, the 25% overload is considered. The overload current can be calculated as:

$$I_{OC} = 1.25 \times I_0 \quad (3)$$

Where I_{OC} is overload current retrieved from entire operating cases, I_O is the maximum load nominal current sensed by protection relay under entire operating cases. The parameter of primary current of CT of each relay is selected by the nearest value above the values of I_{OC}.

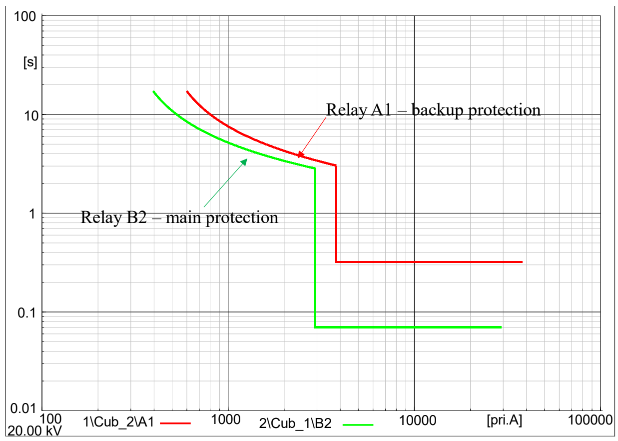

Fig. 7. Time-Current diagram showing the protection relay characteristics.

b) Pickup current setting: Each protection device has two protection elements, overload protection and SC protection. Overload protection (ANSI 51) is implemented via an inverse time curve and the pickup current, which is 2.0-3.0 times the maximum operating current, to ensure the normal operation in case of overload operation. Regarding the SC protection (ANSI 50), it is implemented through a defined time curve. The setting for the feeder protection relay is defined in relation to the minimum expected SC current, $I_{sc,min3P}$, which is the case of a three-phase SC current at the end of the feeder. According to [18], the SC setting of ANSI 50 is defined as 0.9 times the minimum SC current $I_{sc,min3P}$, while it can vary between 1.5 and 3 times the rated thermal current of the feeder line I_{th}. For coordination reasons, the backup protection relay settings will be 1.5 times of $I_{sc,min3P}$ which is higher than the primary relay pickup current. Therefore, the SC setting for the feeder protection relay is defined by*:*

$$I_{FSC} = \max(1.5I_{th}, \min(0.9I_{sc,min3P}, 3.0I_{th})) \quad (4)$$

$$I_{BSC} = 1.5I_{sc,min3P} \quad (5)$$

The defined time for the coordination between main and backup protection is set up, which is 50 ms delay for main protection and 300 ms for backup protection [11]. Based on the pickup current setting, Fig. 7 shows the characteristics with main and backup protection relay when SC occurs at bus 2 in Case 1, and Table IV shows the protection relay configuration coordination in Case 1.

TABLE IV. PROTECTION RELAY CONFIGURATION IN CASE 1.

Short-circuit at	Relay	CT ratio	I_{oc} [A]	ANSI 51	ANSI 50		Short-circuit at	Relay	CT ratio	I_{oc} [A]	ANSI 51	ANSI 50	
				I_r [kA]	I_r [kA]	Delay (ms)					I_r [kA]	I_r [kA]	Delay (ms)
1	B1	1000:1	888	1.42	4.78	50	8	A3b	100:1	84	0.19	1.77	300
2	A1	200:1	170	0.40	3.80	300		B8	100:1	85	0.13	1.06	50
	B2	200:1	169	0.27	2.94	50	9	A8a	50:1	59	0.14	1.72	300
3	A2	200:1	169	0.40	3.63	300		B9	75:1	59	0.08	1.02	50
	B3	200:1	170	0.27	2.26	50	10	A9	50:1	34	0.08	1.59	300
4	A3a	75:1	69	0.16	1.89	300		B10	50:1	34	0.05	0.95	50
	B4	75:1	69	0.11	1.21	50	11	A10	50:1	13	0.03	1.54	300
5	A4a	50:1	49	0.12	1.78	300		B11	50:1	13	0.02	0.92	50
	B5	50:1	49	0.08	1.13	50	12	B12	1000:1	824	1.32	4.92	50
6	A5	50:1	21	0.05	1.54	300	13	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
7	A8b	75:1	23	0.05	1.51	300	14	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

c) Defining direction protection: The directional overcurrent relays of the protection system in the benchmark network is to detect the right operating regions due to a change of its angle in nominal operating cases and isolate the SC and faults. The reference voltage in the MV benchmark system is the voltage at bus 0 with a phase angle of 0°. RTA of Ax and Bx relay in the benchmark system is set respectively at 30° and -30°, with the minimum/maximum forward and reverse angle of the protection system is set as +/- 90° and +/- 90°, respectively.

V. CONCLUSIONS

With the increased integration of RESs in the electrical power grid, there have been increasing challenges for power system protection. This paper comprehensively analyses the CIGRE EU MV benchmark network in the entire operating cases, and two levels of two SC cases, three-phase and single-line-to-ground SC, by using DIgSILENT PowerFactory. The state change of switches in the benchmark network leads to the topologies change, resulting in the different magnitude, the phase angle of the nominal operating current, and the magnitude of SC current. An overcurrent protection aiming to give the complete elements protection is designed with directional overcurrent relays that can be used to isolate the fault and avoid false tripping due to the change of topologies. The method for selecting protection relay configuration settings is also given. This paper contributes with a well-documented and validated overcurrent protection settings of the CIGRE EU MV that can be used for teaching and research purposes. In the case of highly RESs integration into power grid, this paper also provides methodology for protection engineers in analysing network, calculating and selecting proper overcurrent protective relay settings.

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