



INNOVATIONS AND APPLICATIONS OF ARTIFICIAL INTELLIGENCE IN ELECTRICAL AND ELECTRONICS ENGINEERING

Editors

Mohammed WADI

Mohammed SALEMDEEB

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Innovations and Applications of Artificial Intelligence in Electrical and Electronics Engineering

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PREFACE

Artificial Intelligence (AI) has revolutionized various engineering disciplines, providing innovative solutions to complex challenges. *Innovations and Applications of Artificial Intelligence in Electrical and Electronics Engineering* delves into the transformative impact of AI in these fields, highlighting cutting-edge research, advanced methodologies, and practical implementations.

This book comprehensively explores AI-driven advancements, encompassing intelligent control systems, fault detection, predictive maintenance, renewable energy forecasting and optimization, and automation in electrical and electronic systems. The chapters focus on enhancing system efficiency, reliability, and sustainability by integrating AI techniques such as machine learning, deep learning, and optimization algorithms.

Targeted at researchers, academics, engineers, and professionals, this book bridges the gap between AI theory and real-world applications. It presents fundamental concepts and advanced developments, providing insights into AI-powered engineering solutions' latest trends and future directions.

We sincerely appreciate the contributors whose expertise has enriched this first volume. We hope this book is a valuable resource, inspiring further innovation and research in AI-driven electrical and electronics engineering.

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CHAPTER VIII

DIRECTIONAL OVERCURRENT RELAY BASED ADAPTIVE PROTECTION TECHNIQUES FOR DISTRIBUTION NETWORKS

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1. Introduction

Nowadays, electricity distribution networks tend to grow with the increasing the energy demand. Thus, the number of distributed generation sources (DGR) in electricity distribution networks is increasing in order to meet the energy demand. DGRs are known as Renewable Energy Sources (RES) with intermittent operation nature such as wind energy (Wadi et al., 2023), solar energy (Wadi, Jouda, et al., 2024), fuel cells, battery storage systems and other sources. Today, as the number and size of these distributed generation sources increase, electricity distribution networks are evolving to become more reliable and sustainable. Integrating DGRs into distribution networks (DGRs) reduces the dependence of loads on long distance generation sources and helps to minimize transmission losses by reducing the activity of transmission systems. However, DGRs cause some technical problems in addition to the advantages they provide to transmission and distribution systems. These technical problems are; power quality problems (Razmi et al., 2023), adverse load flow (Roy & Pota, 2015), technical losses, grid stability and reliability problems (Ndawula et al., 2019) and protection system difficulties (El Idrissi et al., 2021) stand out. As focused on in this chapter, the difficulties experienced in the protection system of the distribution network with the increase in DGRs; Reverse Power Flow (RPF), increase in short-circuit currents (Meskin et al., 2020), bi-directional power flow (Alcala-Gonzalez et al., 2022), fault impedance and protection blindness (Tariq et al., 2021) and impairment of protection coordination (Yousaf et al., 2021). In particular, with the increase in distributed energy resources, protection coordination structures in electrical grids are becoming invalid.

In order to emphasize the importance of protection coordination, it is necessary to mention the necessity of protection system in the electrical network, its existence is inevitable to ensure human and equipment safety and to continue service continuity. Therefore, the existence of protection systems and the calculation of proper protection settings are seen as a necessity. Therefore, the need for new protection strategies is increasing (Ilik & Arsoy, 2017). In cases where the loads in the distribution network are fed by more than one DGR, protection coordination problems arise in classical protection methods since the load flow and short circuit characteristics of the Distribution Network (DN) change. Therefore, the existence of a dynamic protection system that will quickly solve the protection coordination problems becomes a requirement. This protection system should react selectively, quickly, reliably, economically and determinedly in case of possible short circuit faults of the DN. At this point, the

dynamic protection coordination system in distribution networks should work under realistic constraints for proper protection configurations in cases where protection coordination is disrupted. The use of adaptive protection philosophy, which continues to be popular among dynamic protection systems today, is important in line with these needs (Chandraratne et al., 2018). Adaptive protection systems may have a complex structure depending on the network structure, the number of DGRs, the size of the DGRs, the number of loads and the size of the loads. Based on this, protection coordination in radial DN is simple. Because, the load flow and short-circuit fault currents are unidirectional. However, with the increase in the number of DGRs in the distribution network, the load flow becomes bidirectional. Therefore, the increase in the number of sources at different locations makes the short-circuit fault current bidirectional (Huchel & Zeineldin, 2016). The protection of the network against bidirectional fault currents is provided by directional overcurrent relays that can detect the fault direction (Ataei et al., 2021)(A. Shobole et al., 2018). In meshed distribution networks where there is more than one source, directional overcurrent relays (DOCR) offer the advantage of being simple and economical. In meshed distribution networks with multiple sources, DOCRs enable relay protection coordination with back-up protection and current-direction selectivity (Sharaf et al., 2015). Therefore, since the operating conditions of DGRs will affect the protection system, adaptive protection systems are used. Adaptive protection system should update the protection parameters depending on the magnitudes of load flow and short circuit fault current connected to DGRs. Application of adaptive protection is important for ensuring selectivity and speed criteria in relay protection coordination. Especially, selective and fast protection strategies in severe 3-phase short circuit faults are a critical issue for human health and long equipment life (Wadi, Elmasry, et al., 2024). For this purpose, in order to interrupt unwanted power flow under fault conditions in power systems, circuit breakers (CB) should mechanically open and separate the faulty power system component from the rest of the network. CB are controlled by relays that control CB in the power system. It is easy for relays to control CB. However, implementation of a fast, selective, stable, and economical protection philosophy is considered as an engineering problem.

The organization of the chapter is as follows: Chapter 2 describes the studies in the literature on adaptive protection. The relevant chapter includes comments on the variety of adaptive protection methods. Chapter 3 describes the working principle of Centralized and Distributed Based Adaptive Protection Systems. Chapter 4 describes the tested adaptive protection methods and the test network and network components. Chapter 5 contains adaptive protection

findings based on changing conditions on the test network. Chapter 6 contains conclusions and comments.

2. Literature Review

From past to present, classical and computational methods have been developed for adaptive protection in the literature (Ramlı et al., 2021). Trial and error techniques in the 1960s and curve fitting techniques in the 1980s for classical protection were insufficient for today's distribution networks. Later, one of the classical protection techniques, the protection coordination technique was developed with graph theory. This method is implemented by specifying a relay set that will break all cycles in meshed distribution networks (Matthews et al., 2019). Adaptive protection with graph theory is based on the convergence of relays in all simple cycles to the ideal time multiplier setting (TMS) value with an iterative calculation technique. However, in recent years, mathematical, hybrid and artificial intelligence methods have begun to be used instead of classical protection methods (Khalid & Shobole, 2021). Essentially, adaptive protection is based on updating the protection settings of relays that act as brains in the protection structures of power systems. Protection settings are determined according to the current power system conditions; it is commonly implemented with distance relays (Abdelhamid et al., 2022) and directional or non-directional overcurrent relays.

The popular directional overcurrent protection (DOCR) philosophy in recent years is an important research area for adaptive protection. DOCR is one of the adaptive protection types, determining the relay settings according to dynamic conditions and providing coordination between relays. Directional overcurrent protection coordination is considered as an optimization problem and some methods are presented in the literature to obtain the optimum parameter values. Particle Swarm Optimization (Asadi & Kouhsari, 2009), Cuckoo's Nest Linear Optimization (Dehghanpour et al., 2018), Gravity Search Algorithm (Tripathi et al., 2015) and many optimization methods and protection coordination techniques are presented for directional overcurrent relays. The main aim of these optimization methods is to find the optimum Time Multiplier Setting (TMS) values of the relays and to ensure selectivity in the coordination of protection.

There are remarkable studies on DOCR protection coordination in the literature. ElSayed et al. (ElSayed & Elattar, 2021) used hybrid Harris Hawk optimization method with sequential quadratic programming. They aimed to minimize the total operation time of the distribution system by preventing the

constraint violations determined by this method. The researchers minimized the operation times of the main operating relays and aimed to maximize the operation times of the back-up protection relays until the point where the coordination is broken. Azari et al. (Azari et al., 2022) presented the coordination analysis in the literature using piecewise linear characteristic and non-standard inverse time characteristic in meshed distribution networks. The researchers aimed to minimize all time delays by ensuring the selectivity of the main and back-up protection pairs in the IEEE 14 busbar test system. Akdag and Yeroğlu (Yeroğlu & Akdağ, 2021) used Evaporation Rate Controlled Water Cycle Algorithm (ER-WCA) and Harris Hawk Optimization (HHO) to optimize the nonlinear and highly constrained DOCR coordination. The researchers presented this as an adaptive protection method with a mechanism that limits the fault current by determining the current and voltage index at the fault point in power systems containing DGRs. Draz et al. (Draz et al., 2021) realized the optimum DOCR protection coordination in meshed networks with the Slime Mushroom Algorithm. According to the method in the study, they determined the standard characteristic that calculates the best objective function value of the relay. With the method they used, the researchers concluded that the very inverse and very inverse time characteristics give the best operating time values for DOCR protection coordination. In the literature mentioned above, adaptive protection methods for dynamic changes in DN are quite diverse. Therefore, the best relay operating performances in adaptive protection systems vary according to the network structure and network characteristics. In particular, adaptive protection philosophy is designed in centralized and decentralized models depending on the relay technology. With the advancement of relay technology, it opens a way for the application of decentralized adaptive protection methods.

3. Centralized and Decentralized Adaptive Protection Methods

Nowadays, adaptive protection systems have the advantage of being able to update the configuration of protection relays with the communication infrastructure and a central controller, depending on the status of CB and the network topology.

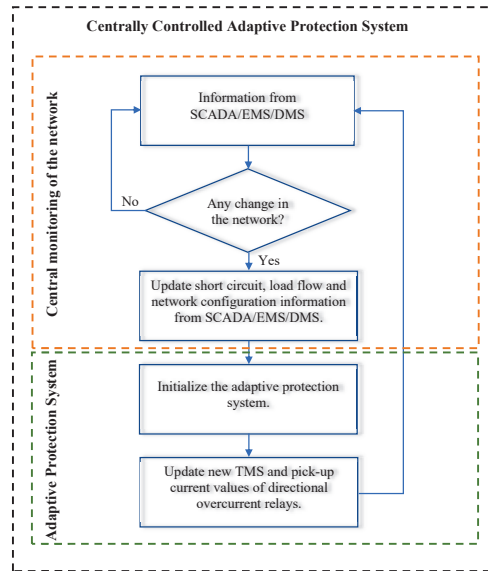


Figure 18. Centrally Controlled Adaptive Protection System.

With the development of the smart grid concept, the communication infrastructure allows numerical relays with advanced protection elements to communicate with fast protocols such as IEC 61850 (Alam, 2019; Memon & Kauhaniemi, 2020). Thanks to the IEC 61850 protocol, software-based numerical relays operate with other relays in real time and with high reliability (Du & Liu, 2012). With this protocol, real-time numerical relays allow dynamic implementation of adaptive protection in DNs. The communication infrastructure has advantages for the use of SCADA (Supervisory Control and Data Acquisition), Energy Management Systems (EMS) and Distribution Management Systems (DMS). SCADA/EMS/DMS allows remote measurement and control of distribution equipment (Storey, 2011). These systems provide real-time analysis tools to the system operator. Thus, distribution systems are operated instantly and more efficiently. Figure 1 shows the real-time adaptive protection system control mechanism. This system updates the protection system based on the functions provided by the SCADA/EMS/DMS system.

Especially new generation digital numerical relays have the ability to exchange information bidirectionally with SCADA/EMS/DMS system in real time. Figure 2 shows a block diagram based on Multi Agent System (MAS) which has the principle of working simultaneously with SCADA/EMS/DMS system.

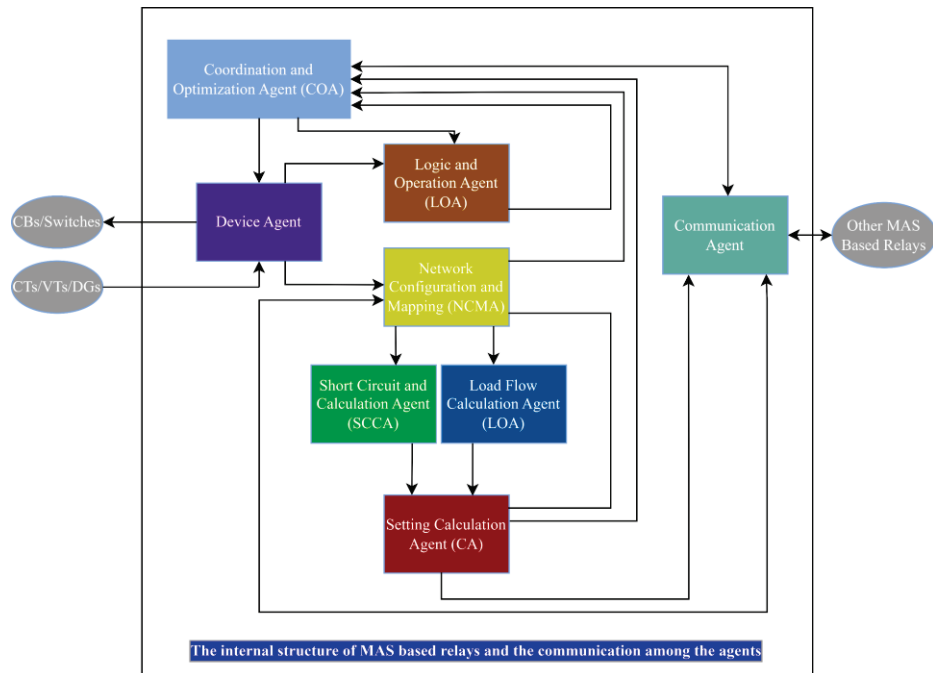


Figure 19. MAS based relay internal block structure (A. A. Shobole, 2022).

In Figure 2, measuring devices such as current transformer and voltage transformer filter the measurement information according to the active or passive status of CBs and digitally transfer it to the smart relay with the logic and process agent. DN is matched with these measurements. Digital relay performs setting calculations according to the standard inverse time overcurrent characteristic according to the load flow and short circuit information. Thus, after the setting calculations are made, the communication agent takes on the role of exchanging configuration information with other relays. Each digital relay is intended to coordinate with the load flow and short circuit information exchanges. In possible short circuit fault scenarios, digital relays are configured with protection coordination settings in accordance with the selectivity and fast operation principle. Thus, the device agent controls the CB and isolates the faulty area for fault scenarios. The advantages of MAS-based systems are that they can exchange real-time information with SCADA/EMS/DMS systems and that even if the measuring devices do not transmit instantaneous measurement information to the digital relays, the measurement information received periodically from DN in the database of the SCADA/EMS/DMS system can be transmitted via the IEC 61850 protocol. Detailed information about MAS based relays is available in (A. A. Shobole, 2022).

4. Proposed Adaptive Protection Coordination Methods

In this section, two methods are presented. The first method is looped adaptive protection coordination system (LAPCS) based on modified graph theory, and the second method is MAS based adaptive protection coordination system (MASAPCS) with communication based bidirectional overcurrent numerical relay (CBBONR) technology. The first method includes the centralized adaptive protection philosophy, while the second method includes adaptive protection coordination based on the operating principle of MAS based relays. Inverse time DOCR equations are given for both methods in Section 4 and proposed adaptive protection methods are introduced in Sections 4.1 and 4.2. According to the standard inverse time characteristic in LAPCS, the convergent ideal TMS values of the relays are found and performance analysis is performed. In the proposed MASAPCS, the TMS value is taken as 0,1 according to the standard inverse time characteristic. The operating time of the primary DOCR is calculated with this method. In the proposed MASAPCS, the working time of the back-up protection relay is found by adding the coordination time interval (CTI) to the working time of the main protection relay. In the conclusion section, the performance comparison obtained from the findings of both systems is made. In this study, near-real-time relay operating performances are analyzed.

The relay configurations of inverse time directional overcurrent relays are made according to the pick-up current (I_p) and time multiplier setting (TMS) regulations. The larger the amplitude of the short circuit fault, the shorter the time required for the relay to generate the trip signal. The main operating relay is selected as the relay farthest from the source and its index is determined as n . The operating time for the main relay is given in Equation (1) according to the inverse time characteristic equation (A. Shobole et al., 2020).

$$t_n = TMS_n \times \frac{\alpha}{\left(\frac{I_{SC,n}}{I_{P,n}}\right)^\beta - 1} \quad (1)$$

Here, the parameters α and β are constants that determine the inverse time characteristic. $I_{SC,n}$ is the short-circuit current magnitude of the main relay n and $I_{P,n}$ is the pick-up current of the main relay n . The standard inverse time characteristic parameters α and β are selected as 0,1 and 0,14, respectively (A. Shobole et al., 2020).

In order to configure a back-up relay that is sensitive to short circuit faults in the protection zone of the main relay, the index of the second relay farthest

from the source is taken as $n + 1$ and its parameters are calculated according to Equation (2).

$$\text{TMS}_{n+1} = \left(\left(\frac{I_{S C_n}}{I_{P,n+1}} \right)^\beta - 1 \right) \times \frac{(t_n + \text{CTD})}{\alpha} \quad (2)$$

The calculated TMS value of the back-up protection relay and the calculation time for faults that will occur in the primary protection zone of the back-up protection relay are calculated according to Equation (3).

$$t_{n+1} = \text{TMS}_{n+1} \times \frac{\alpha}{\left(\frac{I_{S C_{n+1}}}{I_{P,n+1}} \right)^\beta - 1} \quad (3)$$

Relay configurations and protection coordination according to the inverse time characteristic are performed with the equations in Equations (1), (2) and (3). The pick-up current value in Equation (4) is directly related to the load current (I_{LF}) depending on the constant k . In Equation (5), the maximum value that the pick-up current can take depends on the coefficient product of the minimum fault current $I_{SC,min}$ on that line.

$$I_P = k \times I_{LF} \quad (4)$$

$$I_P = s \times I_{S C_{min}} \quad (5)$$

In addition, Equation (6) is given to compare the performance of relay operating times as a result of the relay set values. Equation (6) is used for speed performance testing depending on the selective operation of DOCRs in the power system.

$$\sum_{n=1}^N t_{n,FL} \quad (6)$$

In Equation (6), N represents the total number of relays; FL represents the fault location.

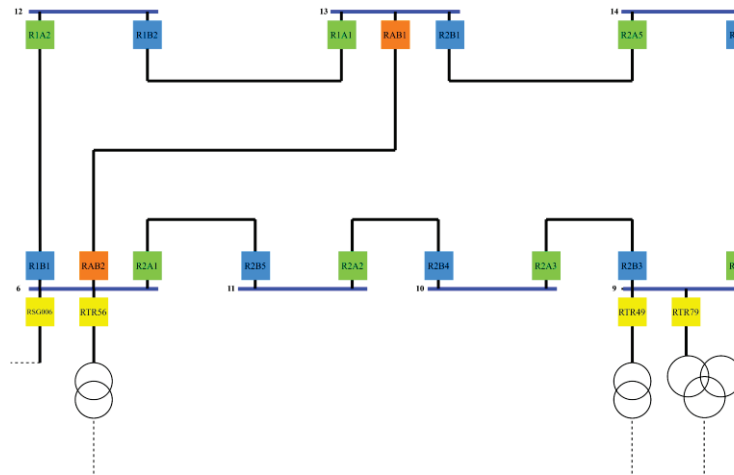


Figure 20. 7 busbar distribution network of IEEE 14 busbar system.

Figure 3 shows the lines protected by DOCRs in the IEEE 14-bus system (*A Data Sheets for IEEE 14 Bus System*, n.d.). Relays RSG006, RTR56, RTR49, and RTR79 are reverse DOCRs, while the other 16-way relays are forward DOCRs. Each relay performs line protection. The reverse DOCRs are positioned to interrupt the short-circuit fault current flowing from the source if the main relays on buses 6 and 9 fail to protect.

4.1. Looped Adaptive Protection Coordination System (LAPCS)

Figure 4 shows each loop that needs to be detected for the loop relay coordination of the test network considered in our study. Each relay is a directional overcurrent relay and provides line protection. Group A forward relays, shown in green, are configured to coordinate protection clockwise, while Group B forward relays, shown in blue, are configured to coordinate protection counterclockwise. Relays RAB1 and RAB2 are shown in orange because they are common forward relays of both loops. The LAPCS in DN is implemented according to the flowchart in Figure 5. This method is achieved by iterating cyclically within the same direction relays with the minimum number of relay sets.

Table 9. Main and backup protection zones of relays.

Relays	Direction of Relays	Main Protection Zone (Line)	Back-up Protection Zone (Line)	Relays	Direction of Relays	Main Protection Zone (Line)	Back-up Protection Zone (Line)
RAB2	Forward	Line 6-13	Line 13-14, Line 12-13	R2A5	Forward	Line 13-14	Line 6-13, Line 12-13
RAB1	Forward	Line 6-13	Line 6-11, Line 6-12	R2B1	Forward	Line 13-14	Line 9-14
R1A1	Forward	Line 12-13	Line 6-12	R2B2	Forward	Line 9-14	Line 9-10
R1A2	Forward	Line 6-12	Line 6-13, Line 6-11	R2B3	Forward	Line 9-10	Line 10-11
R1B1	Forward	Line 6-12	Line 12-13	R2B4	Forward	Line 10-11	Line 6-11
R1B2	Forward	Line 12-13	Line 6-13, Line 13-14	R2B5	Forward	Line 6-11	Line 6-13, Line 6-12, Line 6-12, Line 6-13, Line 6-11
R2A1	Forward	Line 6-11	Line 10-11	RSG006	Reverse	-	Line 6-12, Line 6-13, Line 6-11
R2A2	Forward	Line 10-11	Line 9-10	RTR56	Reverse	-	Line 6-12, Line 6-13, Line 6-11
R2A3	Forward	Line 9-10	Line 9-14	RTR49	Reverse	-	Line 9-10, Line 9-14
R2A4	Forward	Line 9-14	Line 13-14	RTR79	Reverse	-	Line 9-10, Line 9-14

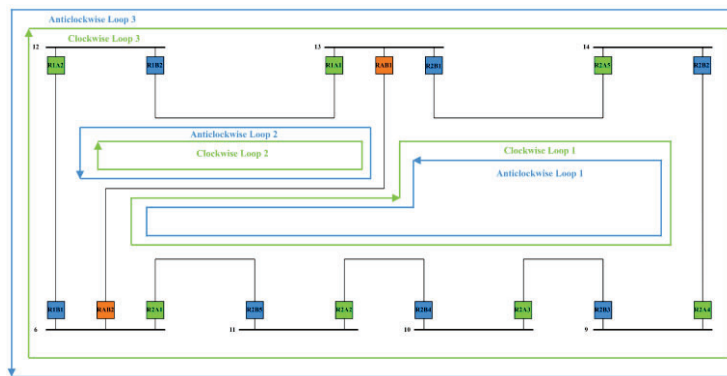


Figure 21. Loops of IEEE 14 busbar test system determined distribution network.

According to this method, the minimum relay set that cuts all loops in the system when opened should be determined. According to the minimum cut set determined in the flowchart in Figure 4, there are a total of 6 loops, 3 clockwise (CW) and 3 counterclockwise (ACW), for the system shown in Figure 4. The minimum cut set relays selected in our study are; R1B1, RAB2 and R2A1 relays. Table 1 shows the DOCRs in each loop of the determined distribution

network of the IEEE 14 test network, while Table 2 shows the clockwise and counterclockwise DOCR sets in Figure 4.

According to the flowchart in Fig. 5, the protection coordination settings of relays for each loop in our centralized adaptive protection method are calculated by the LAPCS algorithm. The pick-up currents of each relay are calculated in the appropriate range and since the line protection is performed, the pick-up currents are selected as a value between 120% of the load current and two-thirds (66.667%) of the minimum short-circuit current.

Table 10. Relay groups of the distribution network determined for LAPCS.

Loops	Relays which in the loops
CW Loop 1	R2A1, RAB1, R2A5, R2A4, R2A3, R2A2
CW Loop 2	RAB2, R1A2, R1A1
CW Loop 3	R2A1, R1A2, R1A1, R2A5, R2A4, R2A3, R2A2
ACW Loop 1	RAB2, R2B5, R2B4, R2B3, R2B2, R2B1
ACW Loop 2	R1B1, RAB1, R1B2
ACW Loop 3	R1B1, R2B5, R2B4, R2B3, R2B2, R2B1, R1B2

According to the algorithm in Figure 5, the TMS value of the minimum cut-off relay is 0,1. According to the flowchart in Figure 5, the operating times of the minimum cut-off relays are a reference for the back-up protection relays. There is a CTI time difference between the main protection relay and the back-up protection relay. This CTI is selected depending on the time and safety factor of the CB (Sookrod & Wirasanti, 2018). According to this method, the ideal TMS values are calculated by iterating the relays according to the standard inverse time characteristic for protection coordination. The iteration ends when the TMS_k value of each relay is equal to the $TMS_{(k-1)}$ value and the coordination of the cycle is completed. Thus, the ideal TMS values are found for each cycle. In this method, the CTI value is taken as 0,3. The constants k and n in equations (4) and (5) are chosen as 1,2 and 0,667, respectively.

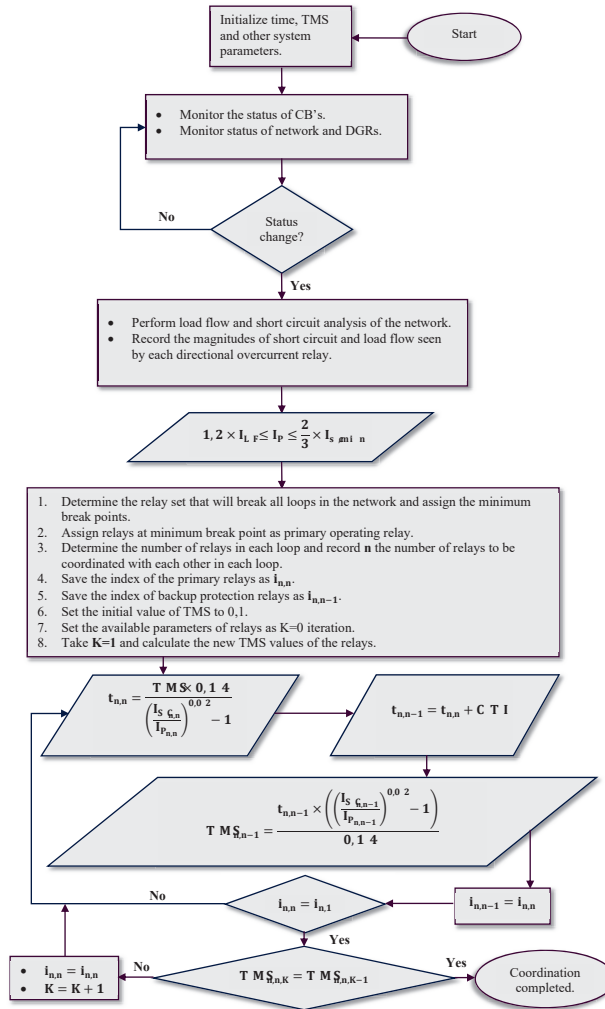


Figure 22. LAPCS algorithm for meshed distribution networks.

4.2. MAS based Adaptive Protection Coordination System (MASAPCS)

The proposed adaptive protection coordination flowchart is presented in Figure 6. The bidirectional overcurrent relay is in the structure of a CBBNOR relay. Figure 6 shows the operating mode selection of the relay in this method as the main protection relay and the back-up protection relay.

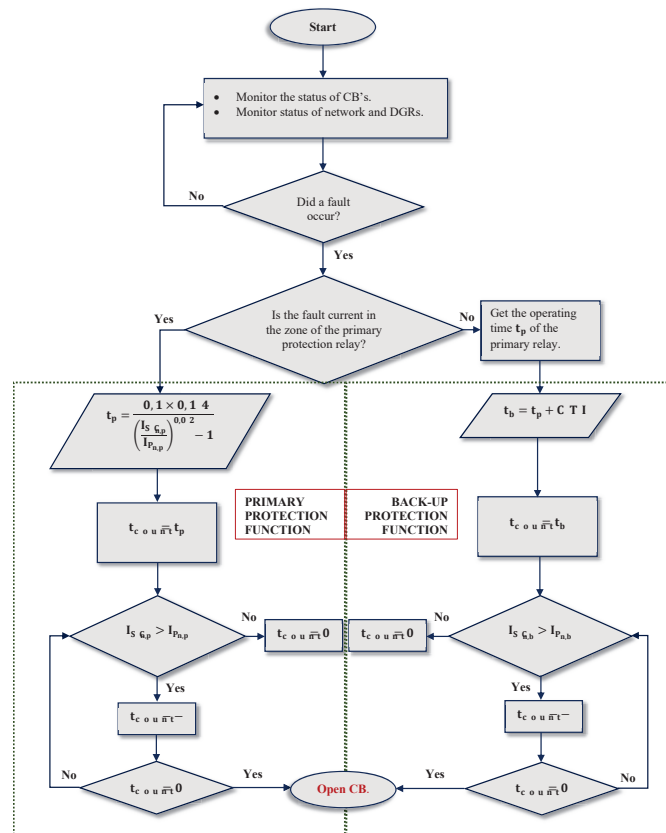


Figure 23. Flowchart of the MASAPCS algorithm.

According to the flowchart in Figure 6, when a short circuit fault occurs at a point in DN, the operating time of the main protection relays is calculated according to the standard inverse time characteristic in the fault area. The TMS value of the main relay is taken as 0,1 and I_p is selected between 1,2 times the load flow current and two-thirds of the minimum short circuit current as in LAPCS. The calculated CB opening time t_p is equal to the counting time t_{count} . The counting time is the operating time of the CB controlled by the relay. If the fault is cleared within the counting time, the relay does not generate a trip signal. During this time, the relay determines that the fault is cleared when the I_p magnitude is greater than the fault current (I_{sc}) and does not give a command to the CB. However, the fault continues as long as the I_{sc} value is greater than the I_p value. If the fault is not cleared within t_{count} , the CB is opened with the operating command. Similarly, the back-up protection function of the relay controls the CB at the end of the period t_b by adding the CTI time to the time information received from the main operating relay.

If the I_{SC} value is less than the I_p value of the backup operation relay, the command is not given by resetting the CB counting time and the fault is cleared. However, if the fault is not cleared at the end of the t_b period, the CB is opened with the opening command.

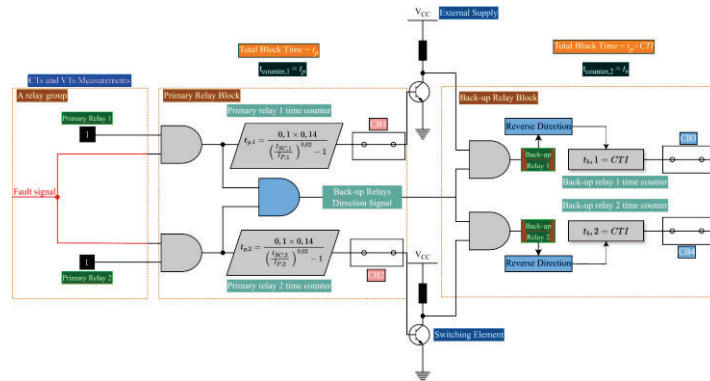


Figure 24. Logical Working Principle of MASAPCS.

In this method, it is important to determine the main and back-up operating relays at the time of fault. The short circuit currents and directions of DOCRs are determined depending on the measurement transformers. Thus, the protection system becomes a distributed structure. The advantage of this method is that it has an independent operating philosophy from the central protection system. If the bidirectional relay protecting the same line sees a short circuit fault, it logically produces "1". The bidirectional relay protecting the same line is selected as the main protection relay. However, if the bidirectional relay protecting the same line does not logically produce "1", it is not selected as the main protection relay. In this case, the main protection relays perform the assignment of the backup protection relay by sending a signal to the reverse DOCR protecting a different line on the same busbar. Back-up protection relays are assigned and backup protection times are calculated.

The logic of determining the main and back-up protection relay according to the MASAPCS method on the distribution network lines determined in Figures 7 and 8 is shown. Table 3 shows the selection of the main and back-up protection functions on the 3 distribution lines taken from the test network determined in Figure 8. In Figure 8, the relays between Lines 6 and 9 are shown to visualize the hardware working principle of the MASAPCS algorithm. Here, Group 1 relays are R2A1 and R2B5, Group 2 relays are R2A2 and R2B4, Group 3 relays are R2A3 and R2B3.

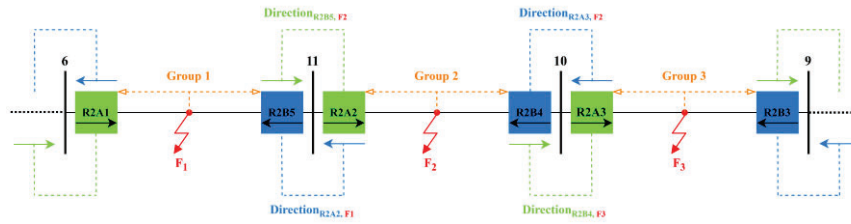


Figure 25. The logic of determining DOCRs as main and back-up relays according to the short circuit fault point in the MASAPCS algorithm.

Table 11. Directional main relay selection during short-circuit fault for MASAPCS.

Group	Relays	The line where the short-circuit fault occurred									
		F ₁	F ₂	F ₃	F ₁	F ₂	F ₃	F ₁	F ₂	F ₃	
		Logically SC presence			Group to work as logic			Back-up protection relay			
1	R2A1	1	1	1	1	0	0	0	0	0	0
	R2B5	1	0	0	1	0	0	0	1	0	0
2	R2A2	0	1	1	0	1	0	1	0	0	0
	R2B4	1	1	0	0	1	0	0	0	1	0
3	R2A3	0	0	1	0	0	1	0	1	0	0
	R2B3	1	1	1	0	0	1	0	0	0	0

According to Figure 8, in the scenario where a short circuit fault occurs between Lines 10-11, relays R2A2 and R2B4 communicate and operate with the "and gate" logic. In the event of a short circuit fault on Lines 10-11, relays R2A1 and R2B3 see the fault, respectively. However, Group 2 and Group 3 will not be main operating relays, because relays R2B5 and R2A3 do not see the short circuit current on Lines 10-11, respectively. In the event of a short circuit fault at point F₂, the relays that perform the backup protection function of Group 2 main relays are directional relays R2B5 and R2A3, respectively. Directional relays R2B5 and R2A3, which protect Lines 6-11 and 9-10, respectively, normally change the protection area in the event of a F₂ fault and generate a trip signal from the main protection relay after the CTI time. The mentioned main and backup relay determination logic has the advantage of being applied independently of the network structure.

5. Results and Discussion

Analyses were performed with two different adaptive protection methods in the 7-bus distribution network of the IEEE 14-bus system. The analyses were performed on 3-phase short circuit faults, which are the most severe fault type.

The TMS and pick-up current values of the relay protection coordination of LAPCS with a centralized protection structure are given in Table 4. Table 5 gives the operating times of the primary and back-up operating relays configured with the LAPCS philosophy at some fault points of the lines.

Table 12. TMS and pickup current setting values of LAPCS.

Relays	TMS (sec)	I _P (s.A)	CTs	CT Ratings	Relays	TMS (sec)	I _P (s.A)	CTs	CT Ratings
RAB2	0,280	4,548	CTAB2	1000/5	R2A5	0,203	3,945	CT2A5	400/5
RAB1	0,280	1,25	CTAB1	400/5	R2B1	0,272	4,19	CT2B1	600/5
R1A1	0,288	4,17	CT1A1	200/5	R2B2	0,322	4,41	CT2B2	200/5
R1A2	0,247	1,333	CT1A2	150/5	R2B3	0,274	4,593	CT2B3	900/5
R1B1	0,248	3,125	CT1B1	800/5	R2B4	0,212	4,251	CT2B4	700/5
R1B2	0,157	3,571	CT1B2	700/5	R2B5	0,145	4,21	CT2B5	600/5
R2A1	0,279	4,875	CT2A1	800/5	RSG006	0,359	4,396	CTSG006	800/5
R2A2	0,213	4,782	CT2A2	700/5	RTR56	0,198	2,883	CTTR56	2000/5
R2A3	0,185	4,632	CT2A3	500/5	RTR49	0,213	4,383	CTTR49	800/5
R2A4	0,216	4,8	CT2A4	700/5	RTR79	0,230	4,873	CTTR79	1400/5

s.A: Secondary Ampere

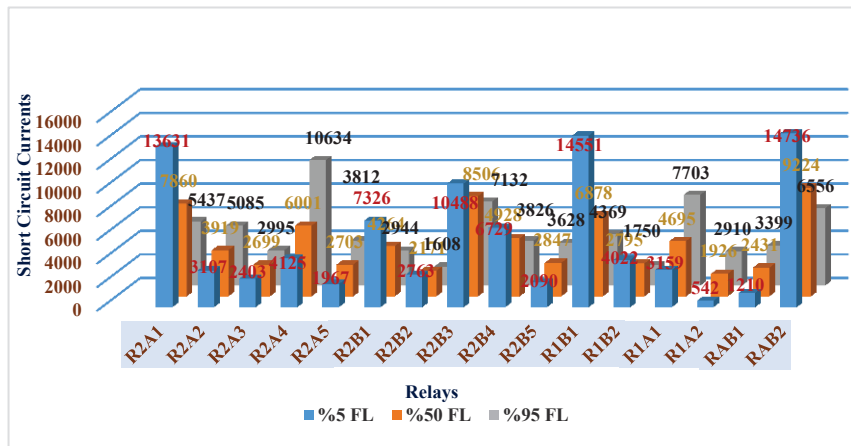


Figure 26. 3-phase short-circuit currents seen by primary protection relays.

Table 5 shows that primary and back-up protection relays provide selectivity, back-up operation, economy, reliability and speed criteria during fault conditions.

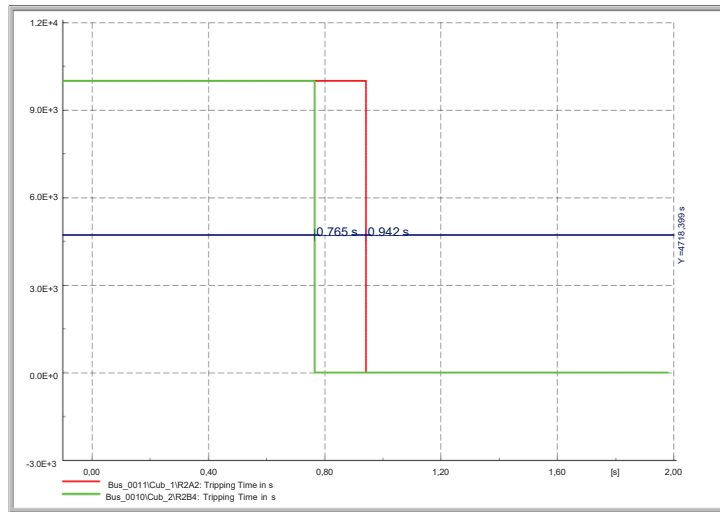


Figure 27. Fault clearing times with LAPCS of main protection relays R2A2 and R2B4 in case of 3-phase short-circuit fault at 50% position of line 10-11.

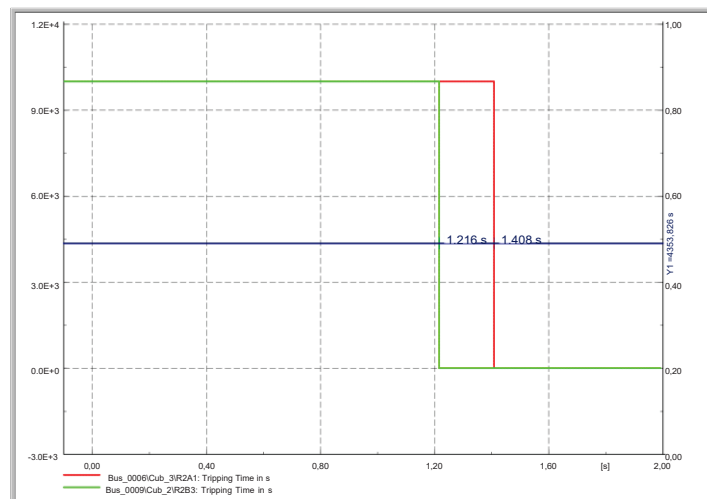


Figure 28. Fault clearing times with LAPCS of backup protection relays R2A1 and R2B3 in case of 3-phase short-circuit fault at 50% position of line 10-11.

Figure 9 shows the short circuit magnitudes seen by the relays at 5%, 50% and 95% length fault points of the lines in the protection zones under normal operating conditions of the system. TMS, short circuit current magnitude and pick-up current value are important for the relays to respond quickly to faults in their primary operating zones.

Table 13. Primary and back-up relays’ operating time at protection zones of IEEE 14-bus system for LAPCS.

Line's Fault Location (FL)	I. Primary Relay	Tripping time of I. primary relay at FL (sec)			I. Back-up Relay	Tripping time of I. back-up relay at FL (sec)			II. Primary Relay	Tripping time of II. primary relay at FL (sec)			II. Back-up Relay	Tripping time of II. back-up relay at FL (sec)		
		5%	50%	95%		5%	50%	95%		5%	50%	95%		5%	50%	95%
Line 6-11	R2A1	0,67	0,83	0,99	R1A2	0,97	2,57	-	R2B5	0,71	0,58	0,51	R2B4	1,17	0,94	0,81
					RAB1	0,94	1,78	-								
					RSG006	1,01	1,27	1,49								
					RTR23	1,02	1,75	3,40								
Line 6-12	R1B1	0,57	0,65	0,79	R2A5	0,80	1,61	2,98	R1A2	0,65	0,56	0,56	R1A1	1,7	0,81	0,69
					RAB1	1,01	-	-								
					RSG006	1,02	1,30	1,51								
					RTR23	1,04	1,83	2,62								
Line 6-13	RAB2	0,69	0,83	0,98	R1A2	1,63	-	-	RAB1	0,94	0,66	0,66	R1B2	-	1,97	0,96
					R2A5	0,78	1,26	2,40					R2A5	0,99	0,88	0,8
					RSG006	1,00	1,17	1,29								
					RTR23	1,00	1,37	1,75								
Line 12-13	R1B2	0,52	0,63	0,87	R1B1	0,82	1,00	1,37	R1A1	0,67	0,66	0,66	RAB2	2,23	1,45	1,03
													R2A5	1,25	1,04	0,81
Line 13-14	R2B1	0,70	0,88	1,06	R1B2	1,00	1,97	5,94	R2A5	0,77	0,65	0,56	R2A4	1,4	1,08	0,86
					RAB2	1,04	1,47	2,05								
Line 10-11	R2A2	0,73	0,84	0,96	R2A1	1,03	1,19	1,40	R2B4	0,79	0,69	0,6	R2B3	1,24	1,06	0,9
Line 14-9	R2B2	0,80	0,88	1,00	R2B1	1,10	1,29	1,62	R2A4	0,82	0,68	0,54	R2A3	11,71	1,63	0,84
													RTR49	3,19	1,85	1,1
													RTR79	2,65	1,73	1,09
Line 9-10	R2A3	0,69	0,73	0,69	R2A2	0,99	1,06	0,99	R2B3	0,88	0,81	0,88	R2B2	1,41	1,2	1,4
													RTR49	1,43	1,23	1,43
													RTR79	1,38	1,21	1,38

EMT/RMS analyses were performed with DIgSILENT PowerFactory software to examine the effects of distribution system frequency and environmental effects on relay performance. EMT analysis results for relay operation stability and visualization of RMS/EMT results with DIgSILENT PowerFactory are available in Figures 10, 11, 13, 15, 16, 17.

Table 14. Primary and back-up relays’ operating time at protection zones of IEEE 14-bus system for MASAPCS.

Line's Fault Location (FL)	I. Primary Relay	Trip time of I. primary relay at FL (sec)			I. Back-up Relay	Trip time of I. back-up relay at FL (sec)			II. Primary Relay	Trip time of II. primary relay at FL (sec)			II. Back-up Relay	Trip time of II. back-up relay at FL (sec)		
		5%	50%	95%		5%	50%	95%		5%	50%	95%		5%	50%	95%
Line 6-11	R2A1	0,23	0,29	0,35	R1B1	0,53	0,59	0,65	R2B5	0,48	0,39	0,34	R2A2	0,78	0,69	0,64
					RTR56											
					R1B1											
					RSG006											
					RAB2											
Line 6-12	R1B1	0,23	0,31	0,39	R2A1	0,53	0,61	0,69	R1A2	0,26	0,17	0,15	R1B2	0,56	0,47	0,45
					RTR56											
					R2A1											
					RSG006											
Line 6-13	RAB2	0,24	0,29	0,34	R1B1	0,54	0,59	0,64	RAB1	0,27	0,21	0,19	R2B1	0,57	0,51	0,49
					R2A1											
					RSG006											
					RTR56											
Line 12-13	R1B2	0,37	0,47	0,69	R1A2	0,67	0,77	0,99	R1A1	0,23	0,2	0,17	RAB1	0,53	0,5	0,47
					R2B1											
Line 13-14	R2B1	0,25	0,32	0,38	RAB1	0,55	0,62	0,68	R2A5	0,37	0,31	0,27	R2B2	0,67	0,61	0,57
					R1A1											
Line 10-11	R2A2	0,4	0,35	0,31	R2B5	0,7	0,65	0,61	R2B4	0,28	0,32	0,36	R2A3	0,58	0,62	0,66
Line 14-9	R2B2	0,24	0,27	0,31	R2A5	0,54	0,57	0,61	R2A4	0,37	0,31	0,24	RTR49	0,67	0,61	0,54
													RTR79			
													R2B3			
Line 9-10	R2A3	0,41	0,39	0,36	R2B4	0,71	0,69	0,66	R2B3	0,26	0,29	0,31	RTR79	0,56	0,59	0,61
													RTR49			
													R2A4			

Two synchronous DGRs (RES) with 20 MVA apparent power and 0,9 power factor were added to Bus 10 and Bus 11 as in Figure 12 to analyze the adaptive responses of LAPCS and MASAPCS methods with the change of active states of DGRs in the system.

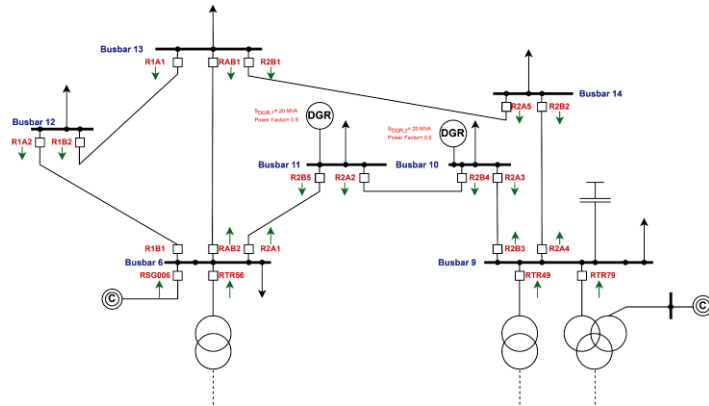


Figure 29. DGR added to IEEE 14 busbar network to test LAPCS and MASAPCS algorithms.

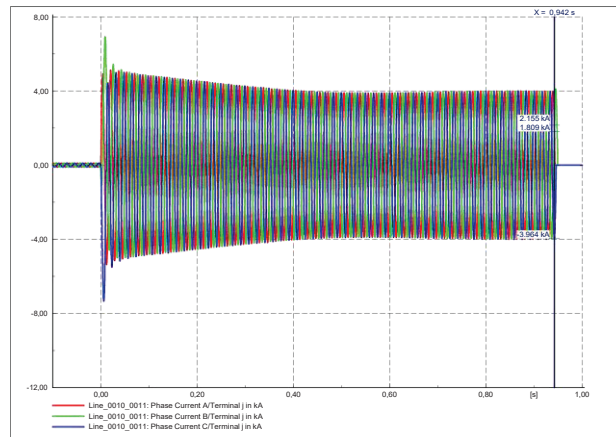


Figure 30. Phase currents variation for 3-phase short-circuit fault of LAPCS at 50% position of Line 10-11.

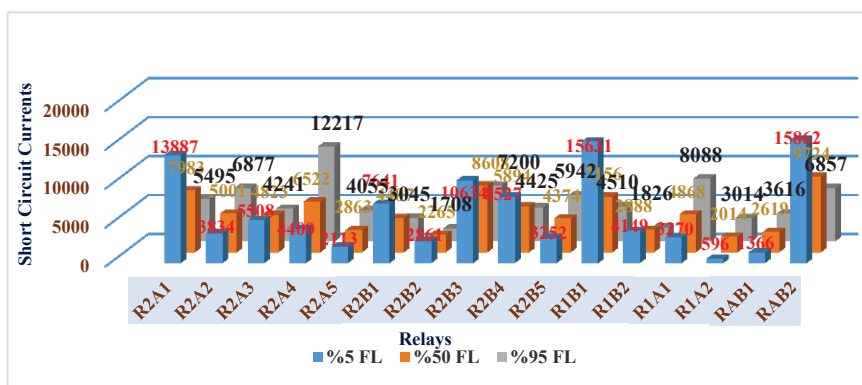


Figure 31. 3-phase short-circuit currents seen by primary protection relays after adding DGRs.

Tables 6 and 10 are given to compare the adaptive protection performance for MASAPCS algorithm; Tables 5 and 7 are given to compare the adaptive protection performance of LAPCS algorithm. Table 8 shows the TMS values calculated by the LAPCS algorithm after adding two 20 MVA DGRs to the test network. Table 9 represents the sample table for the operating performances of the main and backup relays for MASAPCS after adding the DGRs.

Table 15. Primary and back-up relays’ operating time at protection zones of IEEE 14-bus system for LAPCS after adding DGRs into DN.

Line's Fault Location (FL)	I. Primary Relay	Trip time of I. primary relay at FL (sec)			I. Back-up Relay	Trip time of I. back-up relay at FL (sec)			II. Primary Relay	Trip time of II. primary relay at FL (sec)			II. Back-up Relay	Trip time of II. back-up relay at FL (sec)		
		5%	50%	95%		5%	50%	95%		5%	50%	95%		5%	50%	95%
		Line 6-11	R2A1	0,67		0,83	0,99	R1A2 RAB1 RSG006 RTR23		0,97 0,9 3,18 1,03	1,91 1,5 3,18 1,75	- - 3,18 3,37		R2B5	0,74 0,64 0,56	R2B4
Line 6-12	R1B1	0,59	0,67	0,81	R2A5 RAB1 RSG006 RTR23	0,818 1,04 3,18 1,04	1,29 - 3,18 1,93	1,71 - 3,18 2,85	R1A2	0,68 0,61 0,61	R1A1	1,66 0,84 0,72				
Line 6-13	RAB2	0,7	0,85	1	R1A2 R2B5 RSG006 RTR23	1,5 0,79 3,18 1,01	- 1,06 3,18 1,41	- 1,37 3,18 1,84	RAB1	0,81 0,7 0,7	R1B2 R2A5	- 0,97 0,89 0,82				
Line 12-13	R1B2	0,54	0,66	0,89	R1B1	0,84	1,02	1,38	R1A1	0,7 0,7 0,7	RAB2 R2A5	2,27 1,48 1,05 1,26 1,07 0,83				
Line 13-14	R2B1	0,71	0,9	1,09	R1B2 RAB2	1,01 1,06	1,97 1,49	5,31 2,06	R2A5	0,79 0,68 0,59	R2A4	1,4 1,1 0,89				
Line 10-11	R2A2	0,99	0,8	0,74	R2A1	1,58	1,27	1,04	R2B4	0,62 0,72 0,83	R2B3	0,92 1,13 1,38				
Line 14-9	R2B2	1,1	1,25	1,47	R2B1	1,13	1,3	1,61	R2A4	0,85 0,7 0,55	R2A3 RTR49 RTR79	1,95 2,27 2,02 1,27 1,62 1,54 0,85 1,1 1,1				
Line 9-10	R2A3	0,8	0,76	0,71	R2A2	1,23	1,16	1,01	R2B3	0,75 0,82 0,89	R2B2 RTR49 RTR79	1,55 1,06 1,06 1,9 1,19 1,17 2,43 1,31 1,28				

Table 16. TMS and pick-up current setting values of LAPCS adding DGRs into DN.

Number	Relays	TMS (sec)	Number	Relays	TMS (sec)
1	RAB2	0,291	11	R2A5	0,217
2	RAB1	0,307	12	R2B1	0,283
3	R1A1	0,304	13	R2B2	0,335
4	R1A2	0,268	14	R2B3	0,280
5	R1B1	0,258	15	R2B4	0,241
6	R1B2	0,165	16	R2B5	0,200
7	R2A1	0,281	17	RSG006	1,400
8	R2A2	0,249	18	RTR56	0,202
9	R2A3	0,256	19	RTR49	0,308
10	R2A4	0,230	20	RTR79	0,337

Table 17. Operating times of main and back-up relays for 3-phase short-circuit fault at 50% short-circuit point of test line 10-11 after adding DGRs for MASAPCS.

Line	Fault Type	Relay	TMS (s)	I_p (secondary.Ampere)	I_{sc} (A)	$t_{operating}$ (s)
Line 10-11	3-phase	R2A2	0,1	4,782	5001	0,341
		R2B5	-	5,58	3635	0,641
		R2B4	0,1	4,251	5894	0,298
		R2A3	-	5,952	4593	0,598

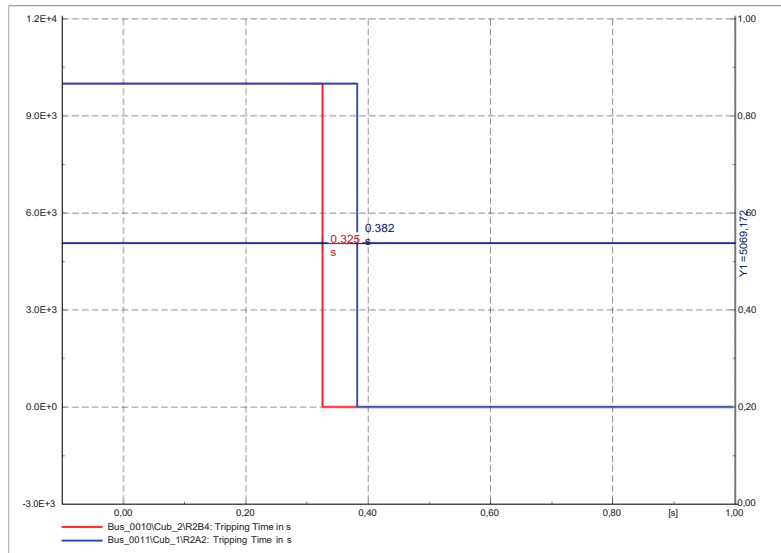


Figure 32. Fault clearing times of the MASAPCS of main protection relays R2A2 and R2B4 in case of 3-phase short-circuit fault at 50% position of line 10-11.

Table 18. Primary and back-up relays’ operating time at protection zones of IEEE 14-bus system for MASAPCS after adding DGRs into DN.

Line's Fault Location (FL)	I. Primary Relay	Trip time of I. primary relay at FL (sec)			I. Back-up Relay	Trip time of I. back-up relay at FL (sec)			II. Primary Relay	Trip time of II. primary relay at FL (sec)			II. Back-up Relay	Trip time of II. back-up relay at FL (sec)		
		5%	50%	95%		5%	50%	95%		5%	50%	95%		5%	50%	95%
		Line 6-11	R2A1	0,24		0,29	0,35	R1B1 RTR56 RSG006 RAB2		0,54	0,59	0,65		R2B5	0,37	0,32
Line 6-12	R1B1	0,2	0,26	0,31	R2A1 RTR56 R2A1 RSG006	0,5	0,56	0,61	R1A2	0,25	0,17	0,16	R1B2	0,55	0,47	0,46
Line 6-13	RAB2	0,24	0,29	0,34	R1B1 R2A1 RSG006 RTR56	0,54	0,59	0,64	RAB1	0,26	0,21	0,19	R2B1 R1A1	0,56	0,51	0,51
Line 12-13	R1B2	0,32	0,39	0,53	R1A2	0,62	0,69	0,83	R1A1	0,23	0,2	0,17	RAB1 R2B1	0,53	0,5	0,47
Line 13-14	R2B1	0,25	0,32	0,38	RAB1 R1A1	0,55	0,62	0,68	R2A5	0,36	0,31	0,27	R2B2	0,66	0,61	0,57
Line 10-11	R2A2	0,39	0,34	0,29	R2B5	0,69	0,64	0,59	R2B4	0,26	0,30	0,34	R2A3	0,56	0,60	0,64
Line 14-9	R2B2	0,25	0,27	0,31	R2A5	0,55	0,57	0,61	R2A4	0,38	0,31	0,25	RTR49 RTR79 R2B3	0,68	0,61	0,55
Line 9-10	R2A3	0,42	0,39	0,37	RTR56	0,72	0,69	0,67	R2B3	0,27	0,29	0,32	RTR79 RTR49 R2A4	0,57	0,59	0,62

Recently, optimization methods for DOCR protection coordination and adaptive protection are frequently used. However, while researchers increase the operating performance of the main relays, the constraint violation occurs when the operating time performance of the backup protection relays is higher than the determined CTI value.

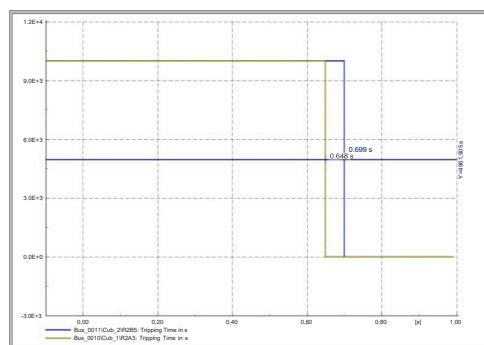


Figure 33. Fault clearing times of the MASAPCS of backup protection relays R2A3 and R2B5 in case of 3-phase short-circuit fault at 50% position of line 10-11.

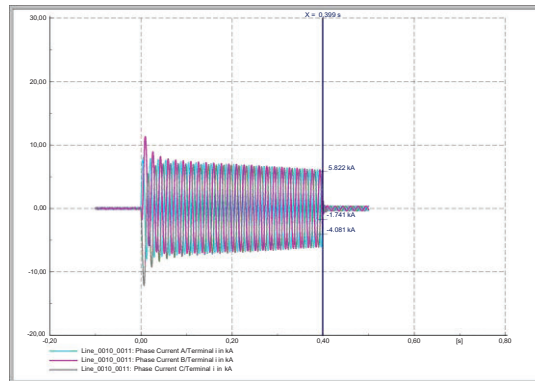


Figure 34. Phase currents change for 3-phase short-circuit fault at 50% position of Line 10-11 of MASAPCS.

In other studies, the main aim is to keep the operating performance of the backup protection relay within the constraints determined by the penalty function depending on the fault location and severity in short-circuit fault scenarios. In the methods presented in our study, the total operating times of the main protection relay are taken into account in the optimization methods, and it is aimed to provide balanced operating performances of the main and backup protection relays for the protection system depending on the fault location in severe short-circuit fault scenarios. In addition, no constraint is needed to test the operating performance of the relays. The reason for this is that after the operating performance of the primary relay is determined, the time signal received for the operating performance of the backup relay is as much as the CTI time value, so a constraint function is not needed.

When the problem is considered as the total operating times of the DOCRs in the distribution network, the relay configurations are compared according to the MASAPCS method as in Table 11. Total operating times of the main relays according to short circuit faults at the near, middle and far points of the line are compared with different protection methods in other studies in Table 11. More detailed analyses are available in detail in study of (TAMYİĞİT, 2022).

Table 19. Comparison of total DOCR trip times of IEEE 14 busbar distribution network with other studies.

Studies	MASAPCS			(Azari et al., 2021)			(Yazdanejadi et al., 2018)			(Sharaf et al., 2015)		
	NFP	MFP	FFP	NFP	MFP	FFP	NFP	MFP	FFP	NFP	MFP	FFP
Σt (sec)	4,97	4,95	5,25	1,6	4,44	6,31	3,1	5,04	7,65	5,75	7,55	10,4
NFP: Near fault point (%5 Fault Location), MFP: Middle fault point (%50 Fault Location), FFP: Far fault point (%95 Fault Location)												

6. Conclusion

The presented adaptive protection algorithms are analyzed on IEEE 14 bus test network with DiGSILENT PowerFactory software and DPL language. LAPCS and MASAPCS algorithms meet all criteria in terms of speed, redundancy, selectivity and economy. However, it is calculated that MASAPCS algorithm clears the fault current 54% faster with main protection relays and 44% faster with backup protection relays compared to LAPCS. Therefore, in Table 11, the operating performances of MASAPCS algorithm are compared with other algorithms in the literature. While MASAPCS algorithm offers simple configuration convenience in complex networks depending on the innovative technologies of digital relays; LAPCS algorithm is a centralized adaptive protection philosophy that responds to dynamic changes in meshed based networks. While MASAPCS algorithm is based on relay technology; LAPCS is based on network type. Although both algorithms have advantages according to network type or relay technology or DGRs number, their operating performances are presented in Tables 5, 6, 7, 10.

Acknowledgment

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