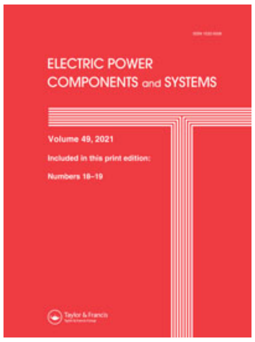

Taylor & Francis
Taylor & Francis Group

Electric Power Components and Systems

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/uemp20

Multi-Agent Systems Based Adaptive Protection for Smart Distribution Network

Abdulfetah Abdela Shobole

To cite this article: Abdulfetah Abdela Shobole (2021) Multi-Agent Systems Based Adaptive Protection for Smart Distribution Network, Electric Power Components and Systems, 49:18-19, 1432-1444, DOI: 10.1080/15325008.2022.2131937

To link to this article: https://doi.org/10.1080/15325008.2022.2131937

Electric Power Components and Systems, 49(18-19): 1432–1444, 2021

ISSN: 1532-5008 print / 1532-5016 online
DOI: 10.1080/15325008.2022.2131937

Taylor & Francis
Taylor & Francis Group

Multi-Agent Systems Based Adaptive Protection for Smart Distribution Network

Abdulfetah Abdela Shobole
Department of Electrical and Electronics Engineering, Istanbul Sabahattin Zaim University, Istanbul, Turkey

CONTENTS

Keywords: adaptive protection, distribution network, distributed generation, over current protection, multi-agent system, self-healing, smart grid

Received 30 December 2021; accepted 13 August 2022

Address correspondence to Abdulfetah Abdela Shobole, Department of Electrical and Electronics Engineering, Istanbul Sabahattin Zaim University, Istanbul, Turkey. E-mail: abdulfetah.shobole@izu.edu.tr

Abstract—The smart power grid has been developed and improved constantly to be able to incorporate protection, automation, communication, and advanced control methods. As a result, the smart power grid system protection is expected to be modernized and given the ability to handle the future complexity that emanates from the integration of Distributed Generations (DGs). An Adaptive Multi-Agent System (MAS) can enhance power system protection and make it more reliable, faster, selective, and robust. In this paper, a novel MAS-based adaptive protection technique that suits smart grid applications is proposed. The proposed protection technique consists of agents that communicate with each other and their environment. The agents used in the proposed technique are Short Circuit Current Calculation Agent (SCCA), Load Flow Calculation Agent (LFA), Setting Calculation Agent (SCA), Logic and Operating Agent (LOA), Coordination and Optimization Agent (COA), and Network Configuration Mapping Agent (NCMA). The proposed technique can adapt to the changing conditions in the smart grid. The DigSILENT PowerFactory software is used to verify the proposed technique using a real Distribution Network in the Antalya vicinity of Turkey. The achieved results show that the method can provide fast and selective protection for the smart grid with increased integration of DGs.

INTRODUCTION

The smart grid is a next-generation power system designed to address the traditional power grid's shortcomings in terms of electricity quality, reliability, efficiency, resilience, and environmental concerns. It is the process of integrating power system infrastructure with information and communication technology (ICT) to automate the grid [1], make it more controllable, resilient, and be able to accommodate power generations from different sources [2–4]. It is primarily defined by its characteristic of bi-directional energy flow, which is the result of the unrestricted integration of Distributed Energy Resources (DERs) [5]. However, the involvement of the bi-directional flow of energy makes the implementation of the smart grid very challenging, as it is faced with technical problems such as power system protection malfunction. Protection system blinding, sympathetic tripping, and over-current protection degradation are

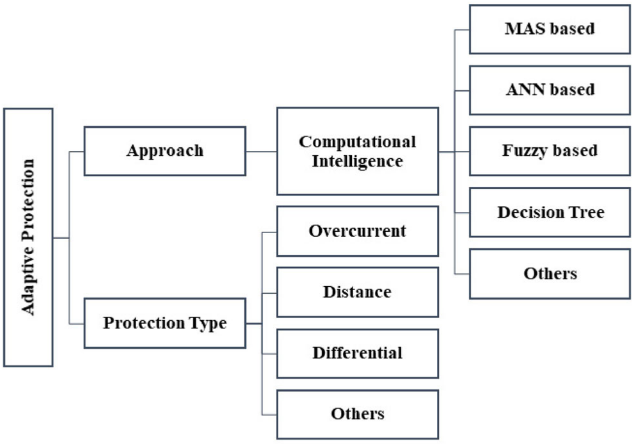

FIGURE 1. The adaptive protection techniques categorized in terms of approach and protection type.

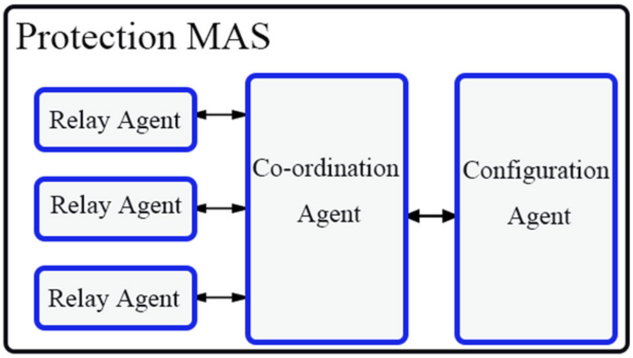

FIGURE 2. The generic MAS architecture for power system protection.

the common challenges caused by the DGs [6–8]. Furthermore, the fault current's considerable dependence on grid operation conditions, type, amount, location, power rating, control type, dynamic behavior, and intermittency of distributed generators (DGs) [9] needs novel smart grid protection solutions. Consequently, the current protection system research trend is on developing adaptive protections [10–13]. The adaptive protection adapts the protection settings of the relays to ensure that they are adequate for constantly changing power system conditions. The main category of strategies utilized in adaptive protection is shown in Figure 1. Advanced and cognitive analytical approaches such as Multi-Agent System (MAS), which can handle complicated analysis, can be used to build adaptive protection techniques. As in the work of Lin et al. [14], there are a small number of research papers on MAS used for adaptive power system protection Non-adaptive protection techniques, on the other hand, can use the MAS method [15].

The research works involving the smart grid that make use of the MAS method are available in several research fields including power system protection and restoration [16, 17], optimal power flow [18], cyber security [19, 20], voltage control [21], micro-grids [22, 23], smart home [24], reliability assessment [25], and energy market [26]. Abdelaziz et al. [27] have discussed an adaptive protection scheme for optimal coordination of the protection relays. The system enables the relays to calculate settings when there is a change in the system. In the work of Alam et al. [28], another adaptive protection and coordination technique is proposed with the addition of using a A Mathematical Programming Language (AMPL) based Interior Point OPTimization (IPOPT) solver. According to the several research works reviewed [29–31], MAS application areas in the power system include monitoring diagnosis, distributed control, modeling and simulation, and power system wide-area protection [32, 33]. Abedini et al. [34] have reported the development of a simulation platform known as Multi-Agent System for Protections Coordination (MAS-ProteC). Daryani et al. [35] have presented a method for treating a relay as a MAS in the presence of DGs, Point of Common Coupling (PCC), Current Transformers (CTs), and Voltage Transformers (VTs). A measurement sub-agent, an operation sub-agent, and a communication sub-agent are recommended for this MAS. To find and clear the fault, a hierarchical MAS with Zone Agent (ZA), Recloser Agent (RA), and Switch Agent (SA) is used. The master agent, the RA, keeps track of reclosers to notify the ZA of the recloser's lockout. The SA receives voltage and current data and communicates with actuators before sending it to the ZA. Kirchhoff's current law is used by the ZAs to assess whether the fault is in their area. For DNs to integrate wind turbines, Lui et al. [36] have presented an adaptive, MAS-based solution. The lowest MAS layer is made up of distributed controller agents and relay agents, such as the DG Agent (DGA), Relay Agent (RA), and Load Agent (LA). The Forward Relay Agent Society (FRAS) and the Back Relay Agent Society (BRAS) are two that represent RAs agents. As explained by George et al. [37], coordination agents, configuration agents, and relay agents are the core components of the general MAS architecture for power system protection Figure 2. The coordination agent locates the issue using the protection types it has installed and determines whether or not the relay should operate. Overcurrent protection, sequence elements protection, distance protection, and differential current protection can all be utilized to detect the occurrence of a defect. The configuration agent determines which relay should be turned on. Even though several studies have revealed similar MAS architectures, it is difficult to define power system protection precisely under the same MAS architectures [6].

The above-discussed research trend shows, the requirement of further works on MAS-based protection. To solve the protection problems caused by DGs integration and bi-directional flow of energy a new MAS-based adaptive protection method is proposed in this paper. Most of the previously proposed researches considered the MAS method as a combination of agents distributed across different parts of the distribution network. However, the currently proposed MAS-based adaptive relays consist of all the necessary agents at each relaying point and can communicate with the other MAS-based adaptive relays located in other parts of the power system network. Moreover, this method solves the coordination degradation that arises from short circuit current variation across the network due to the type and location of DGs. In addition, it is built upon the already available over-current protection technique with more functionalities enabled by using adaptive MAS. Thus, the adaptive MAS-based protection proposed in this work is a novel way of solving the protection problems of the smart distribution grid which emanates from the DGs' intermittency and continues network configuration change.

To verify the proposed MAS-based adaptive protection relays, each agent is implemented to the already available relay models in the DigSILENT Power-Factory by using DigSILENT Programming Language (DPL). The Multi-Agent Systems are designed by adding more functionality to the previously used over-current-based relays inside DigSILENT Power-Factory. The practical applicability of the method at a real Distribution Network in the Antalya vicinity of Turkey is discussed by Shobole et al. [38]. The method works for all operating conditions of the distribution network and DGs' intermittency as discussed in section five.

The following is a breakdown of the paper's structure. The MAS is presented in the second section. The suggested MAS-based adaptive protection approach is extensively discussed in section three. The proposed coordination among the relays implementing the MAS-based adaptive protection is detailed in section four. In section five, the DigSILENT implementation of the proposed adaptive MAS-based protection is discussed. In section six, the conclusion drawn from the work is given.

AGENTS AND MULTI-AGENT SYSTEMS (MAS)

A Multi-Agent System (MAS) is a framework of agents that collaborate to achieve a common goal [39]. Agents are intelligent computer systems that can act autonomously or semi-autonomously and can make critical decisions using local or global information to achieve their design specifications. They can be software, hardware, or a pairing of both [40]. The MAS is made up of multiple smaller programs or pieces of hardware (agents) that are easier to design, maintain and react to changes in the environment quickly. Agents communicate, negotiate, and collaborate with their environment and other agents to make decisions [41, 42]. They also have autonomy, allowing them to operate independently of any control calls from other systems or agents. As a consequence, an agent can be added or withdrawn without impacting the entire system's functionality. Agents are well suited for distributed applications because of their capacities. Reactive agents adapt to changes in their environment, whereas cognitive agents take the initiative to attain their goals [43]. Cognitive agents have a greater capacity to communicate and are more intelligent. Reactive agents, on the other hand, cannot make higher-level decisions and are typically employed in applications that demand quick replies. Whether agents rely on explicit information or models of the environment, they can be reflective. They can also be intelligent and learn if they can enhance their performance based on prior actions and interactions with the environment.

THE PROPOSED MAS BASED PROTECTION TECHNIQUE

The currently used protection relay's internal architecture has to be modified to make it adaptive. In this work, the MAS is proposed to include agents such as the Short Circuit Current Calculation Agent (SCCA), Load Flow Calculation Agent (LFCA), Setting Calculation Agent (SCA), Logic and Operating Agent (LOA), Device Agent (DA), Network Configuration and Mapping Agent (NCMA), Coordination and Optimization Agent (COA), and Communication Agent (CA). In addition, the relay processors are expected to be capable of implementing the MAS method. Due to great advancement in the processors and software sector, it is possible to implement all agents in one physical environment (relays). However, it can also be possible not to implement all the agents in one physical relay to compromise the computational resources. For example, the agents which can calculate the short circuit and load flow currents can be located in a different physical environment for example Distribution Management System (DMS). In Figure 3, the internal structure of the proposed MAS-based full packet adaptive relay is shown, and the detailed discussion of each agent is given in the following subsections.

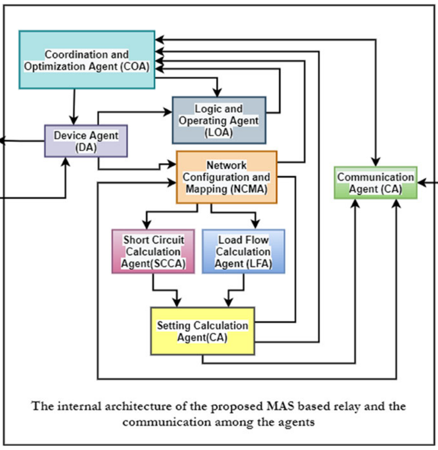

FIGURE 3. The internal architecture of the proposed MAS relay.

Short Circuit Current Calculation Agent (SCCA) and Load Flow Calculation Agent (LFA)

The internal algorithm of SCCA and LFA is shown in Figure 4. These agents are new functions included to make the Intelligent End Device (IED) adaptive concerning the change in the short circuit and load current. The SCCA is concerned with calculating the fault current required for the calculation of protection settings. The fault current calculated by this agent must be sent to the Setting Calculation Agent (SCA). The SCA uses these values to calculate the new protection setting for the relay in coordination with other protection relays. This agent has to calculate the actual fault current for every change that has happened in the network. It requires the power system data such as the different sources' fault current contribution, transmission lines, and cables impedance values, transformers impedance values, and the configuration information of the network. Inside this agent, the short circuit calculation methods such as IEC 60909/VDE 0102, the ANSI, the IEC 61363 for AC short circuit calculation, and the IEC 61660 for DC short circuit calculation can be implemented. Inside the IED which implements this agent, depending on the computational resource available, the short circuit analysis can be simplified to the minimum and maximum fault current calculations only. In the actual operation, if it is not possible to implement calculation of the short circuit and load flow calculation inside the relays, this agent can be configured to get these values from Distribution Management System (DMS). This agent communicates with other agents such as the network Configuration Mapping Agent (NCMA). This helps it to get the connection information of circuit breakers and understand the network configuration.

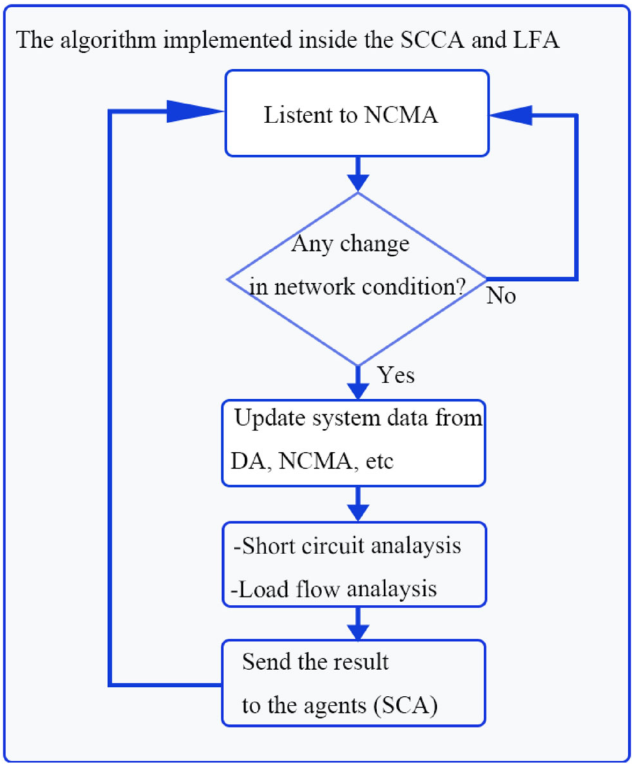

FIGURE 4. The internal logic of the SCCA and LFA.

The LFA is used to calculate the current operating conditions of the power system such as loading of different equipment, voltages of each node, etc. This agent has to conduct a load flow calculation by using methods like the Newton-Raphson method for each change of the network condition, such as opening or closing of switches or circuit breakers. Likewise, loading currents have to be calculated for any change (increase or decrease) in the power injected by the different sources (for example DGs) in the grid. This agent has to communicate with the Network Configuration Mapping Agent (NCMA) to get the actual network configuration data for the load flow analysis. In addition, based on the computational resource available, the level of detail for load flow analysis can be determined. However, at least, the loading current at the particular relaying point has to be calculated and sent to the Setting Calculation Agent (SCA).

Setting Calculation Agent (SCA)

The setting calculation agent is used to calculate the protection setting values automatically for the relay as shown in Figure 5. It uses the information received from the SCCA and LFCA about the fault current and the load flow current respectively. In addition, it has to use the

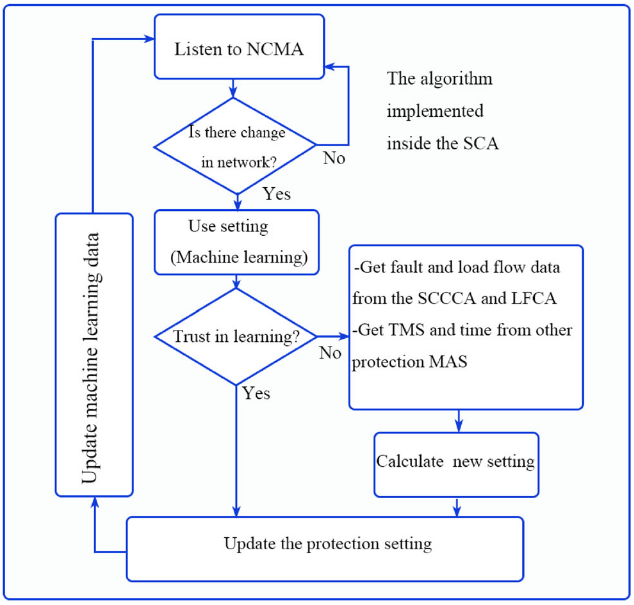

FIGURE 5. The internal logic of the SCA.

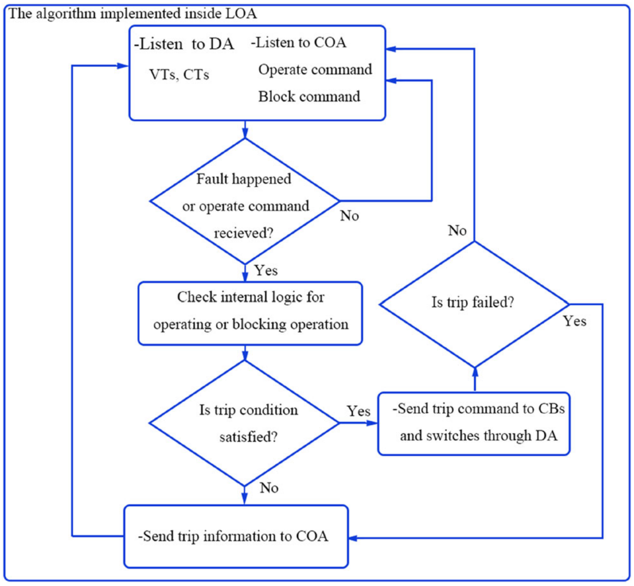

FIGURE 6. The internal logic of the LOA.

information received from the external communication agent to consider overall system conditions such as the time limit from the Transmission System Operators (TSO). In some countries, for example in Turkey, the TSOs put the time limit in which the distribution system has to clear a fault that happened in the DNs before the transmission systems' relay operates at the point of connection of DNs to the transmission system. In Turkey, this time limit is at most 1 second for any short circuit fault that happens in the DNs side. In addition, if the IED is peripheral during automatic setting calculation, then it has to be provided with an optimum time multiplier setting to start the coordination. The calculated settings by the SCA has to be sent to the Logic and Operating Agent (LOA).

In this agent, machine learning algorithms can be implemented to find out the proper setting based on the previously gained experience. The setting calculation results can be used to teach the machine. After the teaching process, the learned settings can be checked, and if it is found reliable, then there is no need to do the setting calculation again. However, if the setting result is found unreliable, then a new setting calculation will be conducted. In this paper the machine learning part is not implemented. It will be implemented under the different scope of the author's future work.

Logic and Operating Agent (LOA)

This agent is used to implement the logic for the operation of the relay and circuit breakers as shown in Figure 6. It uses the setting values received from the Logic and Operating Agent (LOA), and the current and voltage information from the Device Agent (DA). This agent can implement different logical combinations of the trip signals, follow-me signals, and blocking signals received from other relays and circuit breakers. Various programming logic such as AND, OR, NAND, XOR, etc., that were previously implemented in numerical relays can also be realized by using this agent. This agent will send a trip signal to DA to change the status of CBs and switches.

Device Agent (DA)

This agent is used to facilitate the interaction of protection MAS with the other physical device as shown in Figure 7. For example, the LOA requires the actual current and voltage values to determine whether the fault occurred or not. The current and voltage values are measured by current and voltage transformers (CTs and VTs). In addition, the actual loading currents of the power system component such as DGs, loads, etc. are collected by DA. The information about the circuit breakers and switches status (open or close) is collected and organized by the DA. The decision from the other agents, for example, LOA's trip signal is transferred to the devices (CBs and switches) by the DA. The Network Configuration Mapping Agent (NCMA) uses also the information from the DA to determine the actual network configuration.

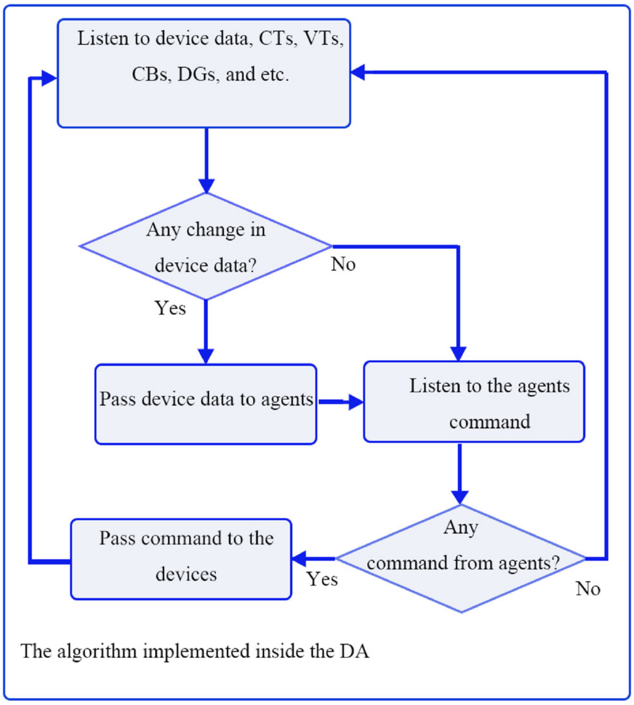

FIGURE 7. The internal logic of the DA.

Network Configuration Mapping Agent (NCMA)

This agent is mainly concerned with mapping any change in the network configuration as shown in Figure 8. In addition, the variation of the integration level of DGs is also mapped by this agent. This agent collects the data required for mapping the network configuration from field devices such as switches, circuit breakers, voltage transformers, current transformers, and DGs through the DA. The NCMA can use the 'xor' logic to detect the change in the network by using switches and circuit breakers' status values. For example, as in the work of Shobole et al. [42], the status of circuit breakers (CBs) 0 for CB open, 1 for CB closed is shown in Table 1. In this case, there is no any change in the status of CBs between times $(t-2)^{th}$ and $(t-1)^{th}$, but at the t^{th} time, CB2 is changed from open position to closed position. The network configuration information from this agent is used by other agents such as SCCA, SCA, and LFCA.

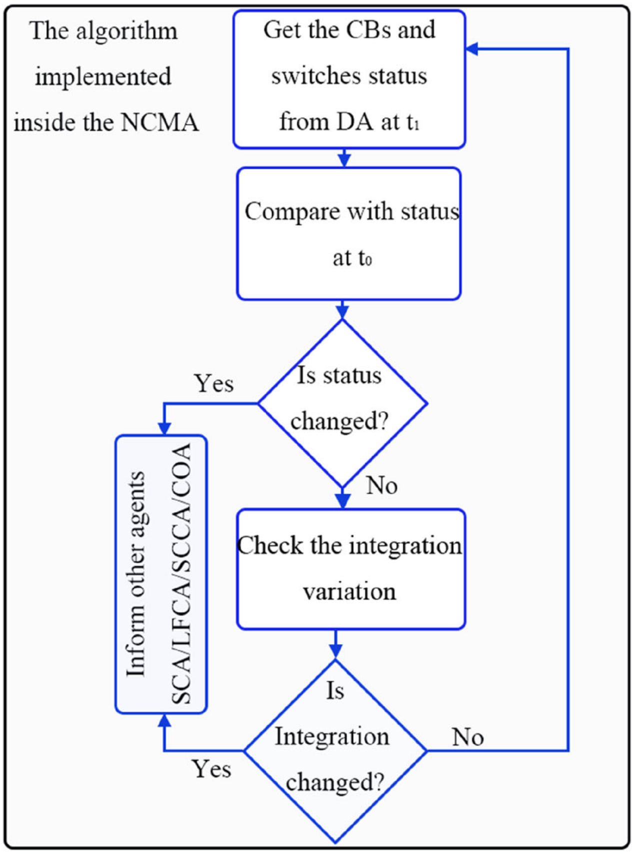

FIGURE 8. The internal logic of the NCMA.

Coordination and Optimization Agent (COA)

This agent is mainly concerned with providing coordination among the relays implementing MAS across the network as shown in Figure 9. It is used to initialize the adaptive protection based on the information received from NCMA. In addition, the time and time multiplier setting optimizations can be handled by this agent. This agent communicates with Setting Calculation Agent (SCA), and Logic and Operating Agent (LOA), to improve the performance of the protection technique implemented inside the relay.

The Multi-Agent System-based adaptive relay calculates the TMS values for the rest of the relays automatically by using the coordination curve formula used. If t_n and TMS_n are the downstream relay's operating time and time multiplier settings respectively, by using IEC normal inverse curve, the operating time t_n can be calculated as:

$$t_n = TMS_n * \frac{0.14}{\left(\frac{I_n}{I_{pn}}\right)^{0.02} - 1} \tag{1}$$

Based on the optimization, a proper grading margin can be selected for the coordination among the protection relays that are coordinated together. Then, the time multiplier setting of an upstream relay can be calculated as follows:

$$TMS_{n+1} = \frac{t_n + CTI}{\frac{0.14}{\left(\frac{I_n}{I_{p_{n+1}}}\right)^{0.02} - 1}} \tag{2}$$

Where: I_n is the fault current for the downstream relay;

Designation	Time	CB1	CB2	CB3	CB4
A	$(t-2)^{th}$	1	0	1	0
B	$(t-1)^{th}$	1	**0**	1	0
C	t^{th}	1	**1**	1	0
A xor B	$(t-1)^{th}$	0	0	0	0
B xor C	$(t-1)^{th}$	0	**1**	0	0

TABLE 1. The status of circuit breakers (CBs) to detect network configuration.

I_{n+1} is the fault current for the upstream relay. $I_{p_{n+1}}$ is the pickup current to the upstream relay; TMS_{n+1} is the time multiplier setting for the upstream relay. The operating time for the upstream relay is calculated as follows:

$$t_{n+1} = TMS_{n+1} * \frac{0.14}{\left(\frac{I_{n+1}}{I_{p_{n+1}}}\right)^{0.02} - 1} \tag{3}$$

In most cases, the distribution networks can be well protected with time-inverse over-current (OC) protection. Based on the fault location, each relay will operate either as a primary relay or as backup relay [1, 44]. If a relay detects a fault in its forward direction, then it may not be clear whether the fault has happened in its primary region of protection or not. The time and TMS calculated by the inverse curve may not be valid especially when the fault current and pickup current variation is not regular, which mostly happens in the smart grid that is supplied from many sources equations i.e. Eqs. (1)–(3). For the operating time to be valid, the short circuit current must be greater than the pickup current. For example, if one side of the network is supplied from the grid with a high current source and there are feeds from the DGs along the path to the other side supplied from the PV-based DG, both the fault current as well as the load current may decrease. In addition, the pickup current which is a multiple of load current may become more than the fault current in the coordination direction. These will lead to the ratio of short circuit current to pick up current to be less than one $(\frac{I_{sc}}{I_p} < 1)$. In such a case, the calculation of operating time and TMS by using the time inverse curve may not be valid, and the primary operating time of lower-level relay with grading margin added on it will be used as shown in Figure 9. Thus, the problem of irregularity of fault current due to various types of DGs will not affect the coordination among the relays.

COORDINATION AMONG THE MAS BASED RELAYS

In this paper, the coordination strategy discussed by Shobole et al. [42] is implemented by the MAS with the technique shown in Figure 9. In this method, a modified directional over-current relay technique is implemented to decide whether the fault happened or not. The coordination among the relay is handled by the exchanging of information such as follow me signals, Time Multiplier Settings (TMS), Coordination Time Interval (CTI), pickup, and short circuit currents. Each relay will use the information received such as operating time and CTI to calculate its TMS value from the lower level relay. After its setting calculation is completed, the same relay will send its operating time and CTI to the upper-level relay which is in the same coordination direction. The coordination among the relays always starts from the relays at sources, DGs connection points, or loads at the periphery of the network. In Figure 10, for example, relays RA02, RA04, RA09, RA10, RB01, RB06 are the relays where the initial coordination starts and will continue toward the source on the other side as shown by blue line or other DGs or loads at the periphery as shown by the green line in Figure 10. The order of coordination for the relays in the Figure 10 is shown in Table 2.

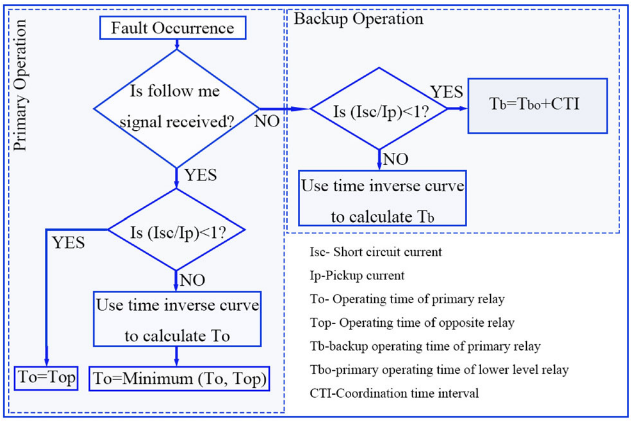

FIGURE 9. The internal logic of the COA.

In this case, the network is considered a ring with a bi-directional flow of energy. Thus, each direction of the flow of energy is treated as a radial network. The coordination among the relay in one direction for example relays RB01 and RB02 will be treated as the same relay in the radial network, and the same method of coordination is applied for the relays which are available in the opposite direction of energy flow, for example, RA10 and RA11. In addition, the relays which are in opposite directions will exchange a follow-me signal and operating times, for example, RA03 and RB07 as shown in Figure 10 by red broken bidirectional arrow.

In the same case, the relay may face difficulty in identifying whether the fault happened in its protection area or

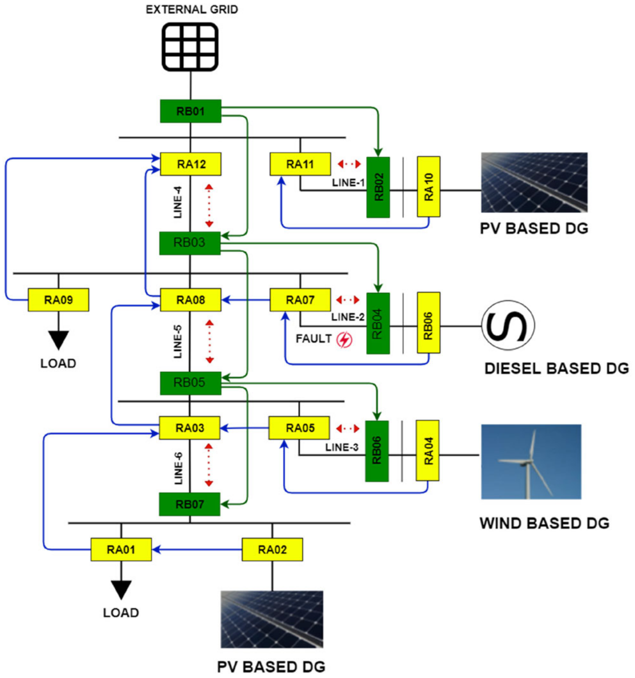

FIGURE 10. The coordination among the relays.

backup protection region. The follow-me signal and operating time exchange among the corresponding relays will serve to solve the coordination problem by using the method shown in Figure 9. If a fault happens as shown in Figure 10 on line-2, the relays RA07 and RB04 will see the fault current in their forward region. If the operating time calculated by these two relays are different, using the follow me signal shown by the bi-directional broken red arrow in Figure 10, the two relays will operate with a faster time.

In addition, if the pickup current is higher than the fault current, which can happen in PV-based DGs due to in-feed from the side feeders, the calculation from the inverse curve may give wrong results. In such cases, the operating time from the opposite relay can be used to clear the fault in the primary region of operation as shown in Figure 9. If the fault is not between the two relays toward the lines (Figure 10), for example, RA07 and RB04, the corresponding relays will not exchange the follow-me signal. However, the relay may see the fault in its forward operation direction, which is an indication of the fault occurrence in the downstream relay and it operates for backup protection. If the fault current variation is even, the inverse curve can be used to determine the operating time, else the operating time of the backup relay will be determined by adding the CTI to the operating time of the downstream relay.

VERIFICATION OF THE PROPOSED METHOD

To verify this method, the Distribution Network with PV-based power plants in Figure 11) in the Antalya Vicinity is used [6]. The maximum short circuit contribution of each solar power plant is 1.5 kA on the 0.4 kV side of the transformer. The PVDG5 and PVDG6 have a 1 MW installed capacity. In addition, 12 wind-based DGs, each with 2.5 MW capacity, are connected ($DG_i - DG_m$, where m is 12). For simulation purposes, each wind-based DG (DG_1-DG_{12}) is connected to the grid systematically 1 MW at a time. This is used to observe how the protection settings of each relay are varied concerning the variation in the integration level of the wind-based DGs. When fully integrated, the total wind energy connected to the grid is 30 MW. The DG_i connected to the C_GES DM 3.1 is out of service. There is also a 20 MW load connected at the DG GES DM 2/B4 bus. During each change in the DGs configuration or integration, each relay automatically adjusted the Pickup values (Tables 3 and 4) as well as the TMS as shown in Figure 12. The TMS values are perfectly graded in the coordination direction of each relay. Figure 12 shows the coordination of TMS for the red direction shown in Figure 11 (RA601, RA602, RAD01 and RAD02). Figure 12 shows the opposite direction of the coordination shown with the green line as shown in Figure 11 (RBD00, RBD01, RBD02, and RB603). The red line coordination is toward the source with a high short circuit current. In this case, the short circuit current increases at the relaying points from RA601 to RAD02. While the green line is the coordination direction toward the DG with a low short circuit current. In both cases, the TMS values for the starting relays (RA601 and RBD00) are initialized with the acceptable value to start the coordination (0.1 is selected). This value must not be less than the minimum possible TMS value of the relay and has to satisfy the time constraint from the transmission line operators at the point of connection of the distribution company (Figure 13).

In addition, faults (F1, F2, and F3) are applied at the different parts of the network as shown in Figure 11. For the fault at F3, the operating time is for each integration under simulation is shown. The fault at F3 will be primarily detected with relays RAD01 and RBD02. For both relays RAD01 and RBD02, the ratio of a short circuit to pick up current for each configuration is greater than one, therefore the operating time automatically calculated by the inverse curve is used. In addition, the relays are operated with minimum time in comparison with the corresponding relays by using the method in Figure 9 and shown by yellow and blue lines in Tables 3 and 4. For example, in

Primary and back-up sequence	1st	2nd	3rd	4th
From the grid side toward other branches	RB01	RB03	RB05	RB07
	RB01	RB03	RB05	RB06
	RB01	RB03	RB04	
	RB01	RB02		
From the other branches toward the grid	RA01	RA03	RA08	RA12
	RA02	RA03	RA08	RA12
	RA04	RA05	RA08	RA12
	RA06	RA07	RA12	
	RA09	RA12		
	RA10	RA11		

TABLE 2. Coordination among the relays.

Table 4, for DGs integration of 2.5 MW, the operating times of corresponding relays RAD01 and RBD02 are 0.539 seconds and 0.735 seconds respectively for the fault (F3 as shown in Figure 11) that occurred in the middle of the line (L3 as shown in Figure 11). But due to the method proposed in Figure 9, the relay RBD02 is not required to wait for 0.735 seconds to operate and can trip with the relay RAD01 at the operating time of 0.539 seconds. This trend is shown in Tables 3 and 4 with yellow and blue colors respectively. For the fault applied at F2, the relays RA502 and RB503 will detect the fault in their forward direction.

The short circuit to pickup ratio of the RA502 relay is greater than one $\left(\frac{I_{sc}}{I_p} > 1\right)$ and the operating time for each integration is shown in Table 4. However, for the relay RB503 short circuit to pickup ratio is less than one $\left(\frac{I_{sc}}{I_p} < 1\right)$. The relay cannot calculate the operating time by using the normal inverse characteristics curve. This is designated by 'INV' to mean invalid operating time calculation in Table 4 under the column $TIME^P$. The relay calculates its operating time $TIME^B$ in Table 4 by using the operating time of the precedent relay in the coordination series. In addition, since relays RA502 and RB503 both see the fault, the relay RB503 can operate by using the time received from the corresponding relay RA502 by using the method in the flow chart indicated in Figure 9.

CONCLUSION

The bidirectional flow of energy due to the integration of DGs can impose a great challenge to the protection system of the smart grid. Therefore, many research works are going on to propose a solution for this challenge. The protection system for the smart grid has to be modified to adapt itself to

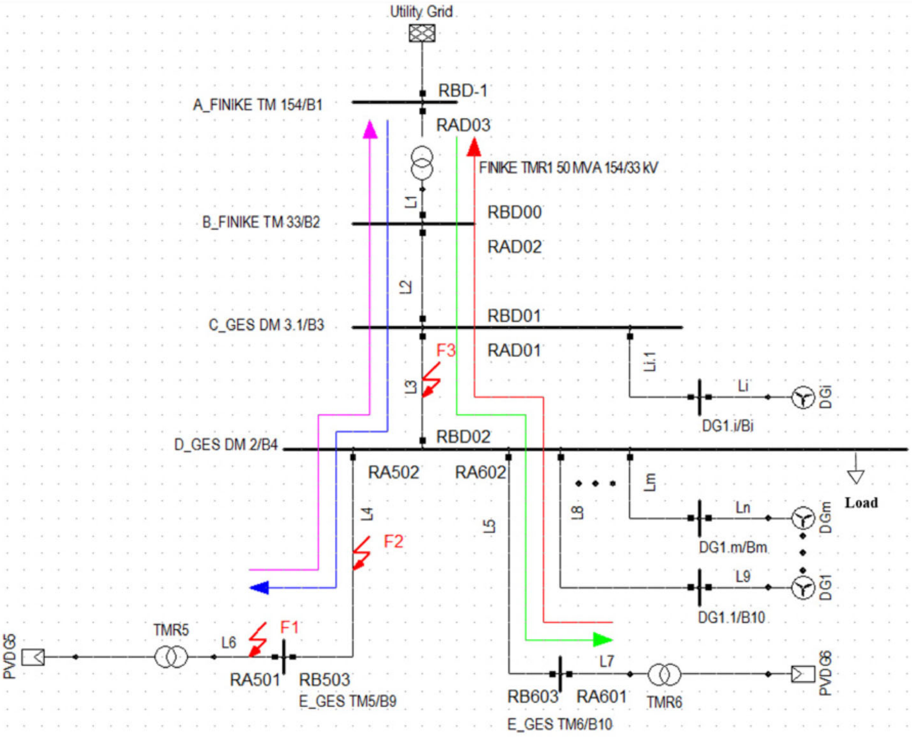

FIGURE 11. The DigSILENT simulation network.

Integration Power (MW)	RAD01				RBD02			
	Pickup Current, I_p (A)	Short-circuit Current, I_{sc} (kA)	$\frac{I_{sc}}{I_p}$	TIME(s)	TIME(s)	I_p (A)	I_{sc} (kA)	$\frac{I_{sc}}{I_p}$
2.5	328.861	5.285	> 1	0.539	0.735	328.861	2.442	> 1
5	275.549	5.285	> 1	0.574	0.631	275.549	4.661	> 1
7.5	222.501	5.285	> 1	0.600	0.586	222.501	6.707	> 1
10	169.706	5.285	> 1	0.615	0.558	169.706	8.592	> 1
12.5	117.153	5.285	> 1	0.621	0.535	117.153	10.330	> 1
15	64.837	5.285	> 1	0.616	0.512	64.837	11.933	> 1
17.5	12.905	5.285	> 1	0.592	0.481	12.905	13.412	> 1
20	39.334	5.285	> 1	0.620	0.494	39.334	14.778	> 1
22.5	91.023	5.285	> 1	0.653	0.508	91.023	16,042	> 1
25	142.563	5.285	> 1	0.679	0.515	142.563	17.214	> 1
27.5	193.942	5.285	> 1	0.704	0.520	193.942	18.300	> 1
30	245.165	5.285	> 1	0.726	0.524	245.165	19.310	> 1

TABLE 3. The operating time for the fault at F3.

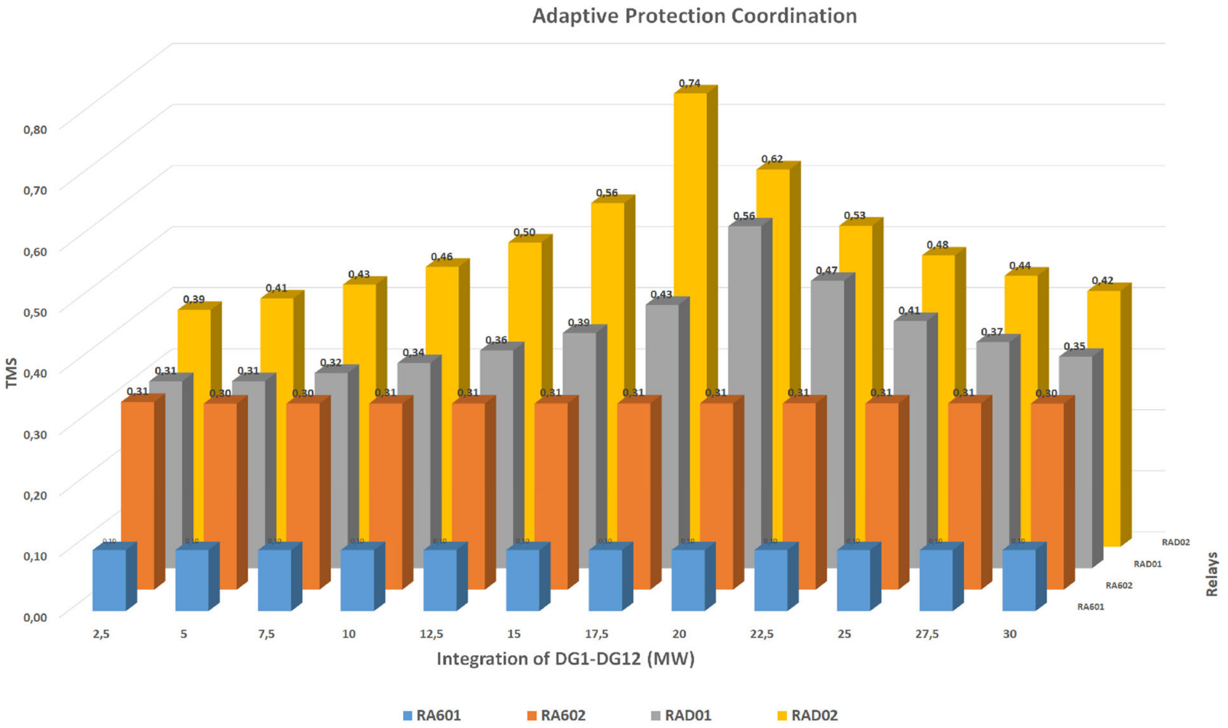

FIGURE 12. The TMS for relays RA601, RA602, RAD01 and RAD02 (Red line on Figure 11).

the continuously changing configuration of the grid as well as the integration of DGs. The adaptive protection which considers different operating conditions and parameters into account requires a new, fast, and reliable computation technique. The MAS-based technique can provide the required fast and distributed computational solution. However, it requires communication infrastructure and more computing resources compared to traditional protection. The cost of this processors is decreasing and their performance is also increasing daily. Even though the increase in power system reliability by using MAS based method is essential, its cost of implementation has to be studied by further research.

In this work, an adaptive MAS-based protection technique is proposed. The proposed technique defines all the functions required for the power system protection by using agents. The agents communicate and exchange the necessary information to provide a fast response during the fault. In the result of this study, the Time Multiplier Setting (TMS), operating time, pickup currents are observed to be correctly calculated automatically

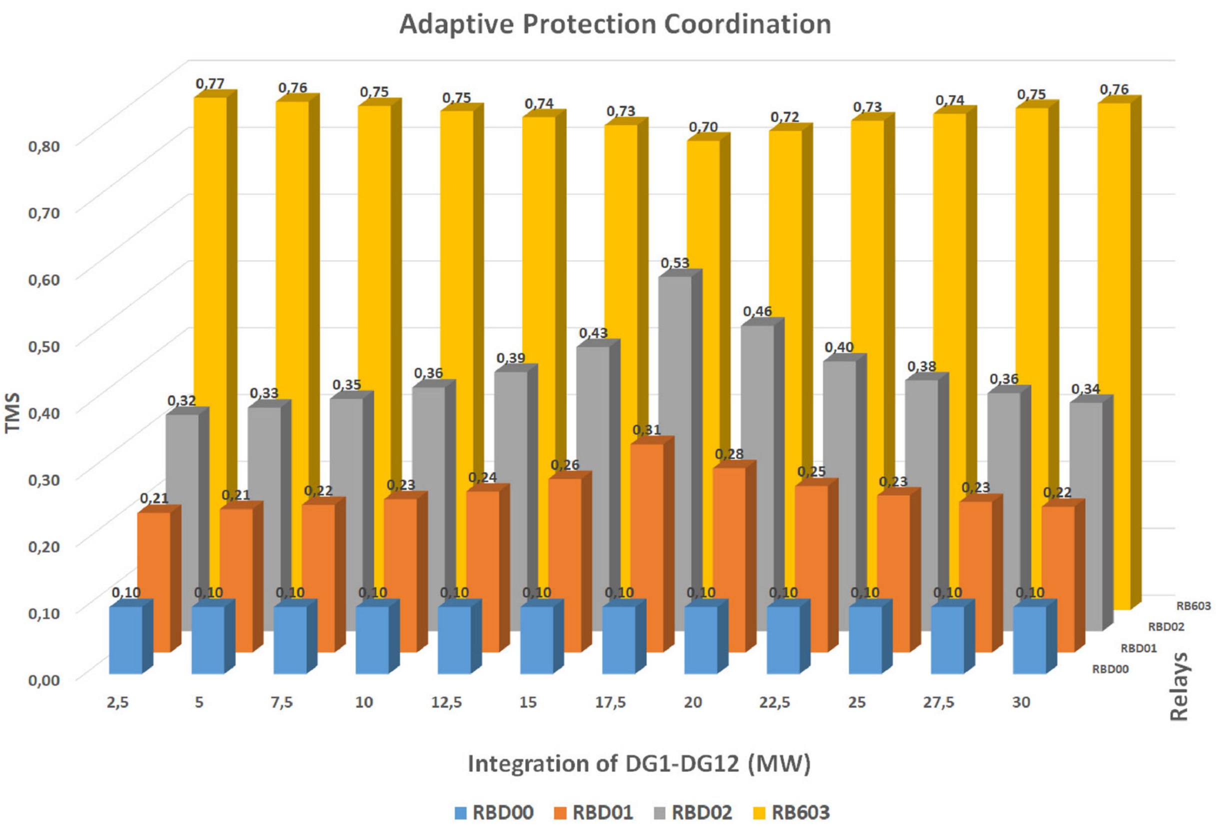

FIGURE 13. The TMS for relays RBD00, RBD01, RBD02 and RB603 (Green line in Figure 11).

Integration Power (MW)	RA502				RB503			
	Pickup Current, I_p (A)	Short-circuit Current, I_{sc} (kA)	$\frac{I_{sc}}{I_p}$	TIME^B (s)	TIME^P (s)	I_p (A)	I_{sc} (kA)	$\frac{I_{sc}}{I_p}$
2.5	21.01	5.981	> 1	0.314	0.735	INV	21.019	0.019
5	20.984	7.594	> 1	0.308	0.631	INV	20.984	0.019
7.5	20.951	9.377	> 1	0.304	0.586	INV	20.951	0.019
10	20.919	11.151	> 1	0.300	0.558	INV	20.919	0.019
12.5	20.889	12.851	> 1	0.297	0.535	INV	20.889	0.019
15	20.861	14.454	> 1	0.295	0.512	INV	20.861	0.019
17.5	20.834	15.954	> 1	0.292	0.481	INV	20.834	0.019
20	20.808	17.354	> 1	0.291	0.494	INV	20.808	0.019
22.5	20.783	18.657	> 1	0.289	0.508	INV	20.783	0.019
25	20.760	19,871	> 1	0.288	0.515	INV	20.760	0.019
27.5	20.739	21.000	> 1	0.287	0.520	INV	20.739	0.019
30	20.718	22.053	> 1	0.286	0.524	INV	20.718	0.019

TABLE 4. The operating time for the fault at F2.

concerning intermittency of DGs and fault current variations. For the fault that happens in the different parts of the test network, the protection relays respond with faster time in a coordinated manner. The results achieved in this work will pave the way for the hardware implementation of MAS-based protection relay. The authors are working on the hardware implementation of the proposed method.

FUNDING

The Author (Abdulfetah Abdela SHOBOLE) is currently running a research work supported by The Scientific and Technological Research Institution of Turkey (TUBITAK) under the project call of " TUBITAK- 3501 - Career Development Program (CAREER)". The work submitted to

this journal is generated from the research work undergoing.

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article.

REFERENCES

[1] Q. Huang, S. Jing, J. Li, D. Cai, J. Wu and W. Zhen, “Smart substation: State of the art and future development,” *IEEE Trans. Power Delivery*, vol. 32, no. 2, pp. 1098–1105, 2017. DOI: 10.1109/TPWRD.2016.2598572.

[2] A. Shobole, M. Wadi, T. U. R. Mehmet Rtda and M. Baysal, “Real time active power control in smart grid,” in *2017 6th International Conference on Renewable Energy Research and Applications, ICRERA 2017*, 2017, pp. 585–590.

[3] D. D. Giustina, et al., “Smart Grid Automation Based on IEC 61850: An Experimental Characterization,” *IEEE Trans. Instrum. Meas.*, vol. 64, no. 8, pp. 2055–2063, 2015. DOI: 10.1109/TIM.2015.2415131.

[4] B. S. Torres, L. R. Ferreira and A. R. Aoki, “Distributed intelligent system for self-healing in smart grids,” *IEEE Trans. Power Delivery*, vol. 33, no. 5, pp. 2394–2403, 2018. DOI: 10.1109/TPWRD.2018.2845695.

[5] G. G. Drankaand P. Ferreira, “Towards a smart grid power system in Brazil: Challenges and opportunities,” *Energy Policy*, vol. 136, pp. 111033, Sept. 2020. DOI: 10.1016/j.enpol.2019.111033.

[6] A. Shobole, M. Baysal, M. Wadi and M. R. Tur, “Effects of distributed generations’ integration to the distribution networks case study of solar power plant,” *Int. J. Renewable Energy Res.*, vol. 7, no. 2, pp. 954–964, 2017.

[7] V. A. Papaspiliotopoulos, V. A. Kleftakis, P. C. Kotsampopoulos, G. N. Korres and N. D. Hatziargyriou, “Hardware-in-the-loop simulation for protection blinding and sympathetic tripping in distribution grids with high penetration of distributed generation,” *IET Conf. Publications*, vol. 2014, no. CP665, pp. 1–3, 2014.

[8] S. E. Razavi, et al., “Impact of distributed generation on protection and voltage regulation of distribution systems: A review,” *Renewable Sustainable Energy Rev.*, vol. 105, pp. 157–167, 2019. DOI: 10.1016/j.rser.2019.01.050.

[9] Y. Wang, G. Wei, H. Yang, H. Chen and Z. Ouyang, “Novel protection scheme of single-phase earth fault for radial distribution systems with distributed generators,” *IEEE Trans. Power Delivery*, vol. 33, no. 2, pp. 541–548, 2018. DOI: 10.1109/TPWRD.2016.2585380.

[10] J. Ma, J. Liu, Z. Deng, S. Wu and J. S. Thorp, “An adaptive directional current protection scheme for distribution network with DG integration based on fault steady-state component,” *Int. J. Electr. Power Energy Syst.*, vol. 102, no. 52, pp. 223–234, 2018. DOI: 10.1016/j.ijepes.2018.04.024.

[11] L. Strezoski, I. Stefani and D. Bekut, “Novel method for adaptive relay protection in distribution systems with electronically-coupled DERs,” *Int. J. Elect. Power Energy Syst.*, vol. 116, pp. 105551, 2020. DOI: 10.1016/j.ijepes.2019.105551.

[12] J. Ma, X. Wang, Y. Zhang, Q. Yang and A. G. Phadke, “A novel adaptive current protection scheme for distribution systems with distributed generation,” *Int. J. Elect. Power Energy Syst.*, vol. 43, no. 1, pp. 1460–1466, 2012. DOI: 10.1016/j.ijepes.2012.07.024.

[13] H. Khalid and A. Shobole, “Existing developments in adaptive smart grid protection: A review,” *Electric Power Syst. Res.*, vol. 191, pp. 106901, Jul. 2021. DOI: 10.1016/j.epsr.2020.106901.

[14] H. Lin, K. Sun, Z. H. Tan, C. Liu, J. M. Guerrero, and J. C. Vasquez, “Adaptive protection combined with machine learning for microgrids,” *IET Gener. Trans. Distrib*. vol. 13, no. 6, pp. 770–779, 2019. DOI: 10.1049/iet-gtd.2018.6230.

[15] J. C. Gu, et al., “Application of multi-agent systems to microgrid fault protection coordination,” in *Proceedings - 2016 IEEE International Symposium on Computer, Consumer and Control, IS3C 2016*, 2016, pp. 188–191.

[16] A. Manickam, S. Kamalasadan, D. Edwards and S. Simmons, “A novel self-evolving intelligent multiagent framework for power system control and protection,” *IEEE Syst. J.*, vol. 8, no. 4, pp. 1086–1095, 2014. DOI: 10.1109/JSYST.2013.2269731.

[17] I. H. Lim, et al., “Design and implementation of multiagent-based distributed restoration system in das,” *IEEE Trans. Power Delivery*, vol. 28, no. 2, pp. 585–593, 2013. DOI: 10.1109/TPWRD.2013.2244923.

[18] R. Kumar, D. Sharma and A. Sadu, “A hybrid multi-agent based particle swarm optimization algorithm for economic power dispatch,” *Int. J. Elect. Power Energy Syst.*, vol. 33, no. 1, pp. 115–123, 2011. DOI: 10.1016/j.ijepes.2010.06.021.

[19] G. N. Ericsson, “Cyber security and power system communication essential parts of a smart grid infrastructure,” *IEEE Trans. Power Delivery*, vol. 25, no. 3, pp. 1501–1507, 2010. DOI: 10.1109/TPWRD.2010.2046654.

[20] T. L. Zhou, K. S. Xiahou, L. L. Zhang and Q. H. Wu, “Multi-agent-based hierarchical detection and mitigation of cyber-attacks in power systems,” *Int. J. Elect. Power Energy Syst.*, vol. 125, pp. 329–334, 2021.

[21] I. Ahmad, P. Palensky and W. Gawlik, “Multi-agent system based voltage support by distributed generation in smart distribution network,” in *Proceedings - 2015 International Symposium on Smart Electric Distribution Systems and Technologies, EDST 2015*, 2015, pp. 329–334.

[22] Y. S. F. Eddy, H. B. Gooi and S. X. Chen, “Multi-agent system for distributed management of microgrids,” *IEEE Trans. Power Syst.*, vol. 30, no. 1, pp. 24–34, 2015. DOI: 10.1109/TPWRS.2014.2322622.

[23] M. S. Elbana, N. Abbasy, A. Meghed and N. Shaker, “µPMU-based smart adaptive protection scheme for microgrids,” *J. Mod. Power Syst. Clean Energy*, vol. 7, no. 4, pp. 887–898, 2019. DOI: 10.1007/s40565-019-0533-6.

[24] T. Labeodan, K. Aduda, G. Boxem and W. Zeiler, "On the application of multi-agent systems in buildings for improved building operations, performance and smart grid interaction - a survey," *Renewable Sustainable Energy Rev.*, vol. 50, pp. 1405–1414, 2015. DOI: 10.1016/j.rser.2015.05.081.

[25] M. A. Da Rosa, A. M. Leite Da Silva and V. Miranda, "Multi-agent systems applied to reliability assessment of power systems," *Int. J. Electr. Power Energy Syst.*, vol. 42, no. 1, pp. 367–374, 2012. DOI: 10.1016/j.ijepes.2012.03.048.

[26] K. Kok, "Multi-agent coordination in the electricity grid, from concept towards market introduction," in *9th International Conference on Autonomous Agents and Multiagent Systems*, 2010, pp. 10–14.

[27] A. Y. Abdelaziz, H. E. A. Talaat, A. I. Nosseir and A. A. Hajjar, "An adaptive protection scheme for optimal coordination of overcurrent relays," *Electr. Power Syst. Res.*, vol. 61, no. 1, pp. 1–9, 2002. DOI: 10.1016/S0378-7796(01)00176-6.

[28] M. N. Alam, "Adaptive protection coordination scheme using numerical directional overcurrent relays," *IEEE Trans. Ind. Inf.*, vol. 15, no. 1, pp. 64–73, 2019. DOI: 10.1109/TII.2018.2834474.

[29] M. J. Ghorbani, M. A. Choudhry and A. Feliachi, "A multiagent design for power distribution systems automation," *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 329–339, 2016. DOI: 10.1109/TSG.2015.2453884.

[30] M. H. Moradi, S. Razini and S. Mahdi Hosseinian, "State of art of multiagent systems in power engineering: A review," *Renewable Sustainable Energy Reviews*, vol. 58, pp. 814–824, 2016. DOI: 10.1016/j.rser.2015.12.339.

[31] F. H. Malikand M. Lehtonen, "A review: Agents in smart grids," *Electr. Power Syst. Res.*, vol. 131, pp. 71–79, 2016. DOI: 10.1016/j.epsr.2015.10.004.

[32] V. Terzija and Y. Liu, "Guest editorial: Special issue on wide area monitoring, protection and control in smart grid," *J. Mod. Power Syst. Clean Energy*, vol. 4, no. 3, pp. 317–318, 2016. DOI: 10.1007/s40565-016-0221-8.

[33] A. G. Phadke, P. Wall, L. Ding, and V. Terzija, "Improving the performance of power system protection using wide area monitoring systems," *J. Mod. Power Syst. Clean Energy*, vol. 4, no. 3, pp. 319–331, 2016. DOI: 10.1007/s40565-016-0211-x.

[34] R. Abedini, T. Pinto, H. Morais and Z. Vale, "Multi-agent approach for power system in a smart grid protection context," in *2013 IEEE Grenoble Conference PowerTech, POWERTECH 2013*, 2013, pp. 1–6.

[35] M. J. Daryani and A. E. Karkevandi, "Decentralized cooperative protection strategy for smart distribution grid using multi-agent system," in *Proceedings - 2018 6th International Istanbul Smart Grids and Cities Congress and Fair, ICSG 2018*, 2018, pp. 134–138.

[36] Z. Liu, C. Su, H. K. Hoidalen and Z. Chen, "A multiagent system-based protection and control scheme for distribution system with distributed-generation integration," *IEEE Trans. Power Delivery*, vol. 32, no. 1, pp. 536–545, 2017. DOI: 10.1109/TPWRD.2016.2585579.

[37] S. P. George and S. Ashok, "Multiagent based adaptive relaying for distribution network with distributed generation," in *2015 International Conference on Energy, Power and Environment: Towards Sustainable Growth, ICEPE 2015*, 2016.

[38] X. Wang, et al., "Interfacing issues in multiagent simulation for smart grid applications," *IEEE Trans. Power Delivery*, vol. 28, no. 3, pp. 1918–1927, 2013. DOI: 10.1109/TPWRD.2013.2260566.

[39] S. D. J. McArthur, et al., "Multi-agent systems for power engineering applications - part II: Technologies, standards, and tools for building multi-agent systems," *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 1753–1759, 2007. DOI: 10.1109/TPWRS.2007.908472.

[40] S. D. J. McArthur, et al., "Multi-agent systems for power engineering applications - Part I: Concepts, approaches, and technical challenges," *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 1743–1752, 2007. DOI: 10.1109/TPWRS.2007.908471.

[41] A. S. Nair, et al., "Multi-agent systems for resource allocation and scheduling in a smart grid," *Technol. Econ. Smart Grids Sustainable Energy*, vol. 3, no. 12018, pp. 1–15. DOI: 10.1007/s40866-018-0052-y.

[42] A. Shobole, M. Baysal, M. Wadi and M. R. Tur, "An adaptive protection technique for smart distribution network," *Elektronika Ir Elektrotechnika*, vol. 26, no. 4, pp. 46–56, 2020. DOI: 10.5755/j01.eie.26.4.25778.

[43] A. Shobole, M. Baysal, M. Wadi and M. R. Tur, "Protection coordination practices for industrial ring distribution network," in *2018 7th International Conference on Renewable Energy Research and Applications (ICRERA)*, vol. 5, 2018.

[44] A. Shobole, M. Baysal, M. Wadi and M. R. Tur, "Protection coordination practice in electrical substation part-1 overcurrent and earth fault protection case study of Siddik Kardesler Substation (SKS), Istanbul, Turkey," *Gazi University J. Science*, vol. 30, no. 4, pp. 180–198, 2017.

BIOGRAPHY

Abdulfetah Abdela Shobole is an Assistant Professor in the Electrical Engineering Department at Istanbul Sabahattin Zaim University. He has been working in the industry in substations, wind farms, solar power plants, and transmission and distribution networks since 2011. His research area includes smart grid protection, cyber security, smart grid automation, and renewable energy integration with the smart grid.