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Multi-Agent System-Based Hierarchical Protection Scheme for Distribution Networks With High Penetration of Electronically-Coupled DGs

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ABSTRACT With the increasing penetration of distributed generations, preserving the protection system coordination is of great importance for the distribution network operation. This paper presents a supplementary protection strategy for the multi-agent system (MAS)-based hierarchical protection scheme (HPS). The primary level of MAS-based HPS clears the fault and preserves the protection coordination while the higher levels update the relay settings. The key advantage of the proposed supplementary scheme is that the primary level can autonomously and quickly preserve the protection coordination when the main relay is during the time-consuming process of updating settings in the case of network operating condition change. By adopting converter-based DGs as the only MAS agents, the proposed supplementary scheme divides the distribution network into several zones that communicate together using point-to-point communication. Without communicating with higher protection levels, the supplementary protection limits the influence of DGs on the fault current by controlling the produced power of each zone. The effectiveness of the proposed strategy is validated through several simulation case studies on the Isfahan distribution network.

INDEX TERMS Distributed generation, hierarchical protection, multi-agent system, protection coordination, supplementary protection.

I. INTRODUCTION

Enhancing the power quality and reliability, developing the efficient and clean energy, increasing the power production, and obviating the power transmit limitation lead to a paradigm change of power system structure from centralized generation to the distributed one [1]–[4]. However, distributed generators (DGs) such as wind turbine generator (WTG) units affect the performance of existing distribution networks depending on their ratings and locations [5], [6]. Preserving the protection system coordination as one of the main requirements of such networks may be disrupted due to the presence of DGs [7]–[9]. This disruption results in the protection devices either do not detect fault condition or wrongly trip the circuit breakers. One of the main reasons for protection system miscoordination is the effect of DGs on the network fault current; the fault current can be so high that the backup protection wrongly trips or it may go out of the operating range of the main protection [10], [11]. Likewise, the change of network current direction may disrupt the protection coordination.

The protection miscoordination problem can be solved by mitigating the DG effects on the distribution system during the fault condition [12]–[14]. The proposed solutions in the literature can be categorized into two groups: (i) methods based on managing the DG operation, and (ii) modified protection system schemes. First group mainly employs four strategies: (1) tripping DGs [15], (2) limiting DGs ratings [16]–[19], (3) locating DGs [20], [21], and (4) managing DGs fault currents [22]–[25]. Fast disconnection of all DGs before the protection system operation is proposed in [15] that results in loss of a lot of loads. In [16], the specific

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penetration level of DGs that leads to the miscoordination of the protection system is calculated. By solving the optimal power flow and optimization problems, [17]–[19] determine the acceptable size of DGs from the perspective of preserving protection system coordination. Ref. [17] uses the mathematical equations of protective devices to set up protection coordination and to calculate the threshold value for the maximum size of DG, beyond which the protection coordination is lost. Ref. [20] proposes a method to preserve the protection coordination based on the DG location. In this method, various fault and DG locations are studied to determine the proper location of installing DGs for reducing the protection system miscoordination. However, it needs high calculations that make this method impractical for large distribution networks with many DGs. Using the genetic algorithm, [21] determines the optimal location of DGs to maximize their penetration level without protection miscoordination. Ref. [22] proposes to use a controllable impedance for controlling the fault current in various operating conditions of the network. Superconducting fault current limiters are employed in [25] to mitigate the impact of DGs on the protection system and to restore the protection coordination. Several control strategies are proposed for converter-based DGs to prevent their current injection to the faulty section. However, when the network structure changes, the settings of protection relays should be updated [23], [24].

The second group uses three main strategies: (1) changing protection system [26], [27], (2) using adaptive protection [28]–[30], and (3) employing intelligent protection [31]–[33]. In [26], by replacing network reclosers with microprocessor-based ones, the coordination between fuse and recloser is preserved in a system with high penetration of DGs. Using the communication links among protection devices is another method for preserving the protection coordination in the presence of DGs. In [27], the distribution network is divided into several zones and is equipped with the breakers that are remotely controlled by the main relay. The faulty zone is isolated by opening the proper breaker and disconnecting the respective DG. The high cost of communication infrastructure for long distances is the main disadvantage of this method. In adaptive protection strategies [28], [29], using a pre-defined algorithm, the protection devices protect the distribution network in various operating conditions such as change of network topology, increase/decrease of DGs penetration level, load change, change of network mode of operation from grid-connected to islanded, and various fault conditions. The centralized processing server of [30] adaptively updates the protection settings of directional overcurrent relays using the evolution algorithm. However, implementing an adaptive protection system requires offline calculations for all operating conditions to consider a specific group setting for protection relays for each network operating condition change. Developing the distribution network increases the complexity of these calculations and make this method impractical in some networks.

The development of intelligent electronic devices (IEDs) helps to solve the protection coordination problem. Recently, multi-agent system (MAS) based methods are employed for preserving the protection system coordination [31]–[37]. A MAS is a communication platform that is designed based on the network goals. In this system, with the help of information collected from the network, decisions are made to manage the performance of network sections. An agent is electronic equipment that can collect information about power grid equipment and perform computational processes. It also can communicate with other agents for receiving and sending signals through a communication network [38]. By selecting the various network equipment such as DGs, relays, and loads as the agents, [31] preserves the protection coordination using a multi-level hierarchical protection scheme (HPS). In [34], a two-level protection structure is proposed using the multi-agent systems. In the first protection level, by using IEDs, some functions are defined in the relays to preserve the protection coordination. While in the second protection level, by receiving the data from the main network agent, DG agents detect the faults. In [35], by changing the characteristic curves of the relay, a protection scheme is developed to preserve the protection coordination among overcurrent relays when the fault current level changes. In [36], by using the less used capabilities of the relays, a protection system is proposed that can replace the available protection system during emergency conditions and the occurrence of a problem in the updating process of protection settings. In [37], a selective protection scheme is proposed for microgrids. In this strategy, by considering the location of IEDs and feeder characteristics, the faulty zone is detected.

However, in addition to the network topology change, continuous change of penetration level of WTGs makes it necessary to frequently update the relay settings by the MAS based HPS. The processes of transferring and processing of network information and updating relay settings are time-consuming; for nowadays' practical relays, this process may take several seconds [31]. If a fault occurs suddenly during updating relay settings, the protection coordination may be lost. Also, the dependency of the protection devices operation to a control center degrades the reliability of the MAS based HPS. To address these issues, this paper presents supplementary protection for improving the performance of MAS based HPS. The proposed method employs the distributed (point-to-point) communication structure and MAS technology and can autonomously make fast decisions during a fault condition. In this scheme, WTGs are adopted as the only agents and they communicate together locally and remotely. It divides the distribution network into several zones and assigns identification (ID) numbers to WTGs. The proposed scheme manages each protection zone by a master agent and increases the

TABLE 1. Comparison between Proposed Protection Scheme and Some Existing MAS based Protection Strategies.

	[34]	[35]	[36]	[37]	[31]	Proposed
Type of agent	RA,DGA,MGA*	RA,DGA,BA,LA	RA	RA,DGA,LA	RA,DGA,BA,LA	DGA
No need for central unit	Yes	No	No	Yes	No	Yes
No need for change of protection system	No	No	No	No	No	Yes
No need for auxiliary relay	Yes	Yes	Yes	Yes	No	Yes
No need for change of protection settings	Yes	No	Yes	No	No	Yes
Type of MAS structure	Point-to-point mode	Hierarchical mode	Hierarchical mode	Point-to-point mode	Hierarchical mode	Point-to-point mode

*RA: relay agent, DGA: DG agent, MGA: main grid agent, BA: breaker relay, LA: load relay.

reliability by selecting an alternative master agent in the case of failing the main one. It mitigates the influence of converter-based WTGs on the protection system by controlling the generated power of WTGs. Table 1 compares the features of the proposed protection strategy and the above-mentioned MAS based protection schemes.

The proposed supplementary protection scheme can simultaneously provide the following features:

- Employment of minimum number of agents and reduction of a variety of agents;
- No dependence on a central processing unit;
- No need for changes of characteristic curves and settings of relays;
- No need for replacing the protection system and no need for directional and adaptive relaying;
- No need for an auxiliary relay in the vicinity of each main relay;
- No dependence on rating and location of DGs;
- No need for disconnection of DGs during a fault condition; and
- Implementation of the proposed method on the point-to-point mode communication structure rather than using the hierarchical structure.

The rest of the paper is organized as follows. Section II investigates the influence of WTGs on the protection system coordination. MAS-based HPS is presented in Section III. Section IV is dedicated to the proposed supplementary protection scheme. The performance of the proposed strategy on a simulation model of a test system is evaluated in Section V. Discussion is presented in Section VI. The conclusions of this work are summarized in Section VII.

II. INFLUENCE OF DGs ON THE DISTRIBUTION NETWORK PROTECTION

In a distribution network, the short circuit current (SCC) level depends on the short circuit power of the upstream network [39]. By determining the maximum load and SCC level of the network, the protection devices are set to properly operate during the fault condition. The distribution networks are protected using circuit breakers, commonly triggered by the overcurrent relays. Based on the standard IEC 60255, the characteristic curve of this relay is expressed as [40]

$$t = \left(\frac{A}{\left(\frac{I_F}{I_P}\right)^P - 1} \right) \times TMS, \tag{1}$$

where I_F is the fault current, I_P is the pickup current, and TMS is the time multiplier setting of the relay. The constant parameters A and P are adopted based on the type of relay characteristic curve.

Regarding the increment of network loads and the importance of providing high power quality to supply sensitive loads, WTGs are introduced to the distribution networks. However, the connection of WTGs to the distribution network changes its short circuit current. Depending on the distance of WTGs to the upstream network and the fault location, they may improve the protection system coordination or in most cases, they disrupt this coordination. If the protection system coordination is lost, the coordination time interval (CTI) of protection devices is not properly satisfied during the fault.

To investigate the effect of full-scale converter-based WTGs on the fault current seen by the relays, the sample system of Fig.1 is studied. It is divided into three protection zones in which R1, R2, and R3 relays protect zone 1, zone 2, and zone 3, respectively. R1 is the backup relay of R2 and R2 is the backup relay of R3. Loads of zones 1, 2, and 3 are 600 kW, 800 kW, and 1000 kW, respectively. The impedances of the network are: $Z_1 = 0.013+j0.014$, $Z_2 = 0.361+j0.396$, $Z_3 = 0.542 + j0.594$, and $Z_4 = 0.009 + j0.009\ \Omega$. WTG current I_{WTG} is equal to 991 A. Since the primary source dynamics are decoupled from those of the network by using a large DC link capacitor [41], [42], the dc link voltage will remain almost constant during short transients, and therefore, WTG is modelled using a constant DC source with the associated converter [43], [44].

In the case of no WTG in the network (WTG current $I_{WTG} = 0$), the R1 (backup) and R2 (main) relay currents for a fault at point F are calculated as [7]

$$I_{grid} = I_{R1} = I_{R2} = \frac{V_G}{Z_1 + Z_2 + Z_3 + Z_4}, \tag{2}$$

where I_{grid}, I_{R1}, and I_{R2} are the network, relay 1, and relay 2 currents, respectively, and V_G is the network voltage. Z_1 is

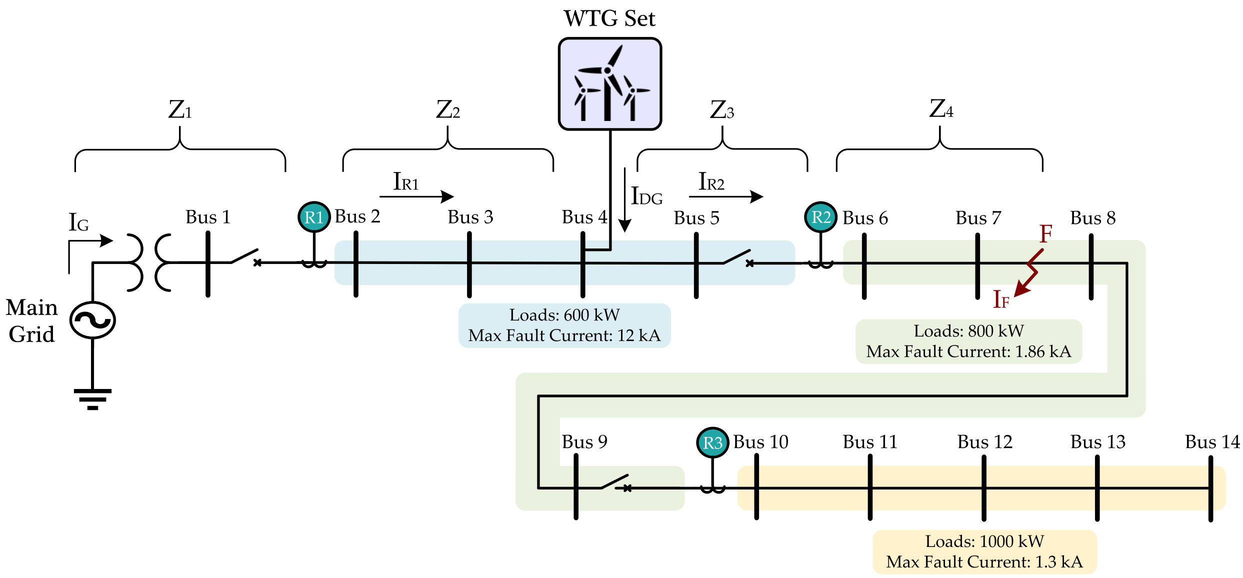


FIGURE 1. Sample study system.

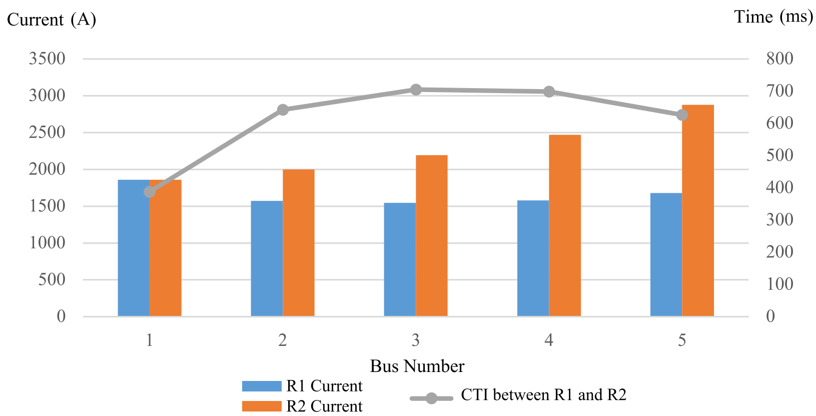


FIGURE 2. Performance of protection system in the presence of WTGs located inside zone 1.

the network impedance, Z_2 is the impedance between WTG and backup relay, Z_3 is the impedance between WTG and main relay, and Z_4 is the impedance between main relay and fault point. When WTG is connected to the network, the network current seen by the backup relay is calculated using the superposition theorem. The new network current is calculated as [7]

$$I'_{grid} = \frac{V_{grid}}{Z_1 + Z_2 + Z_3 + Z_4} - \frac{I_{WTG} \times (Z_3 + Z_4)}{Z_1 + Z_2 + Z_3 + Z_4}. \quad (3)$$

Thus, the backup relay current is expressed as

$$I_{R1} = I'_{grid} = I_{grid} - \frac{I_{WTG} \times (Z_3 + Z_4)}{Z_1 + Z_2 + Z_3 + Z_4}. \quad (4)$$

Equation (4) shows that when the WTG location is changed between the main and backup relays, the current through the backup relay changes by $I_{WTG} \times (Z_3 + Z_4) / (Z_1 + Z_2 + Z_3 + Z_4)$.

The main relay current is expressed as

$$I_{R2} = I_{grid} + \frac{I_{WTG} \times (Z_1 + Z_2)}{Z_1 + Z_2 + Z_3 + Z_4}. \quad (5)$$

When the WTG location is changed between two relays, the main relay current increases by $I_{WTG} \times (Z_1 + Z_2) / (Z_1 + Z_2 + Z_3 + Z_4)$.

If the penetration level of integrated WTGs into the distribution network increases, WTGs output currents I_{WTG} increase. Based on (4), it results in the fault current seen by the R1 relay which is the injected current of the main grid decreases compared to the case of no WTG in the distribution network; the current reduction value depends on WTG location. On the other hand, based on (5), R2 current is always increasing; the amount of this increment depends on the WTG location too. To investigate the effect of WTGs on the distribution network, two wind turbines with the rated capacity of 10 MW are connected to the network. Fig. 2 shows

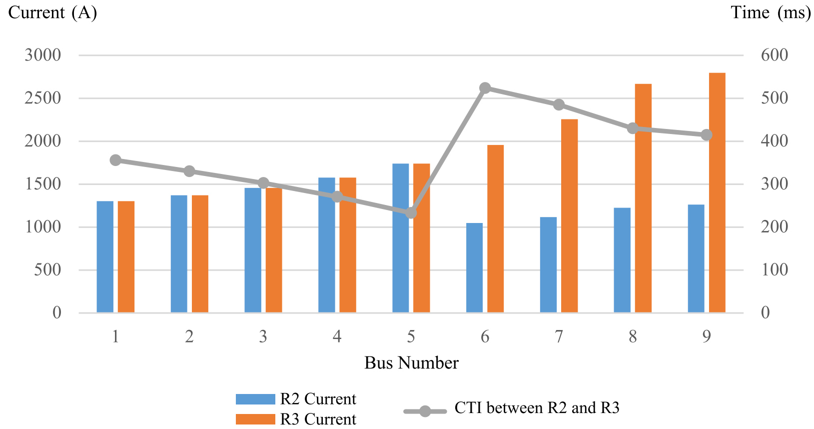


FIGURE 3. Performance of protection system in the presence of WTGs located inside zones 1 and 2 and occurring the fault at zone 3.

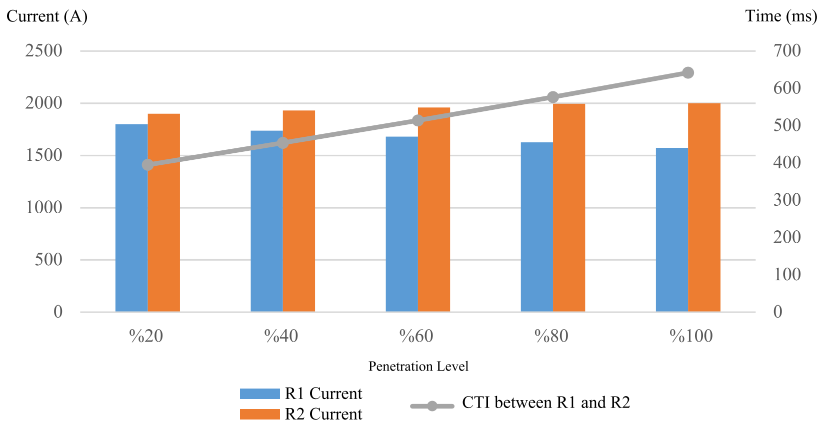


FIGURE 4. Performance of protection system in the presence of WTGs located at bus 2 and change of penetration level of WTGs.

the fault current and operating time of R1 and R2 relays when the fault occurs inside the main protection zone of R2. When WTG distance to the main relay R2 reduces, R2 current is continuously increasing. It should be noted that when WTG is located near the fault and the main relay, the current increment is significant. On the other hand, R1 current in all WTG locations is lower than that in no WTG case. This reduction is less when the WTG is located near the fault location, as shown in Fig. 2 when the WTG is connected to bus 4 or bus 5.

Fig. 3 shows the performance of R2 and R3 relays in the case of a fault inside the protection zone of R3. In this case, WTG location changes from upstream of the main and backup relays to the bus located near the fault. When WTG is located upstream from both relays, the protection coordination is preserved and there is no significant change in the current of relays. However, when WTG approaches backup relay, the protection coordination is lost and when WTG is between the backup and main relay, backup relay current significantly reduces that it results in the slower operation of this relay and miscoordination of the main and backup relays. When WTG is located near the fault point, the backup relay current increases that it improves the CTI.

The effect of change of penetration level of WTGs on the protection coordination in the case of a fault in the main protection zone of the R2 relay is shown in Fig. 4. Assuming a fixed location for WTGs at bus 2, the penetration level of these generators changes. Fig. 4 shows that when the penetration level increases, the current of R2 increases while R1 current decreases. When the penetration level is 20%, R1 and R2 operate coordinately. However, for the penetration levels of 40% and higher, the protection coordination loses. In this condition, the proper settings should be achieved to restore protection coordination.

III. MULTI-AGENT SYSTEM BASED HIERARCHICAL PROTECTION SCHEME

A. MULTI-AGENT SYSTEMS

An agent is a hardware or software entity that autonomously reacts to changes in its environment. It takes the decision based on the received data from the network and other agents and performs a pre-defined function [45], [46]. The agents are installed on an IED and they require an infrastructure including communication links and protocols. The communication protocols make agents capable of transmitting data over the communication channels based on a certain policy and of receiving sent data by other agents. The communication protocol may be dedicated to a message exchanged between two agents for doing a certain task [45], [46]. To make a proper decision, the agents should communicate together to receive the network condition. A multi-agent system is formed when two or more agents work in an environment.

To make the communication links among agents for transferring data, the standard IEC 61850 is employed [31] that defines the communication protocols for intelligent electronic devices at electrical substations. This protocol is designed based on the generic object-oriented substation event (GOOSE) technology in which the network equipment is considered as an element. One of the main capabilities of this technology is to make a direct link between two network equipment for exchanging information. Based on this protocol, the data is transmitted within a time of 4 ms. To increase reliability, this protocol can divide a physical network into several sections by making virtual local area networks (VLANs) and set the appropriate message priority level [47].

B. HIERARCHICAL PROTECTION SCHEME

Using the MAS structure is a protection solution designed for the networks with many changes. So far, many protection schemes have been proposed that are based on this structure. On the other hand, unlike adaptive methods, the advantages of smart devices are their data exchange fast speed, possibility of independent operation, and collection of information from the network. In MAS based methods, each agent, in the form of software or hardware that is located in an IED, acts as a command implementer that can perform specific functions.

MAS based HPS considers the network equipment such as WTGs, relays, and loads as the agents and categorizes the protection functions into multi-protection levels. In the MAS based three-level HPS proposed in [31], the primary protection level aims to clear the fault and to preserve the protection coordination. Updating the relay settings using the predefined lookup table and modifying this lookup table based on some functions are the tasks of secondary and tertiary protection levels, respectively. This scheme employs the distributed communication among agents in which those agents that are close together communicate locally while the communication between far agents is remote. Fig. 5 shows the MAS based hierarchical protection scheme.

To preserve the protection coordination among protection devices in various operating conditions of the network, MAS based HPS collects the network information using the agents of the primary protection level. Then, the higher protection levels analyze and evaluate the sent data by agents using the communication links. Finally, the control center receives the information to take an appropriate decision and sends it to the protection relays. However, this scheme has the following disadvantages.

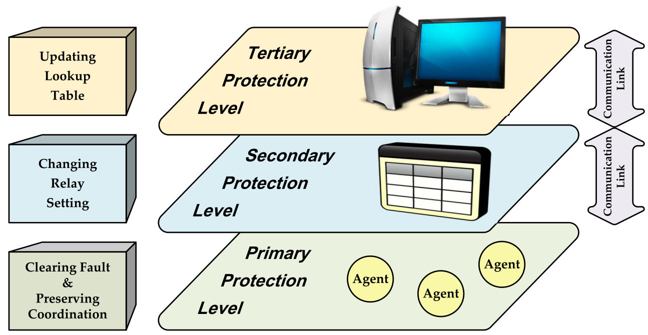


FIGURE 5. MAS based three-level HPS.

- When a fault occurs, the required time for collecting and analyzing the information and for taking and sending the decision can be so high that the protection system does not properly operate.
- When an event occurs, the control center adopts the proper settings and sends them to the relays. In addition to the required time of transferring this information, the relays should update their protection settings and they should be restarted. In addition to the topology change, the operating condition of the distribution network frequently changes due to changes of WTGs penetration level; consequently, the relay settings should be frequently updated. Since updating and restarting the nowadays' practical relays take several seconds [31], if a fault occurs suddenly during this process, the protection coordination may be lost.
- The performance of the MAS based HPS is dependent on the proper operation of the control center. Developing the distribution network increases the agent numbers and consequently exchanged information through communication channels. The increased calculations may result in miscalculation or failure to find any setting for the relays in the control center. Since preserving the protection coordination needs a central decision-maker, its failure may cause the miscoordination of the MAS based HPS.

The purpose of this paper is to provide a solution that solves the problem of conventional hierarchical MAS. The hierarchical structure can be implemented in different networks (loop, low voltage, high voltage,...) [48]–[50]. In each network, the implementation of the protection scheme can be different; accordingly, the type of policy set for the operation of the MAS is also different. In a MAS based protection scheme, the main issue is to recognize the network requirements, because the type of interaction of agents is dependent to the environment in which they are located and it is necessary to manage them for satisfying the network requirements (protection system in this paper). The proposed scheme of this paper keeps the structure of the conventional MAS, but helps to solve its problems; so that there is no need for changing the relay type, changing the relay settings at the fault instant, or additional relays in the network. Most importantly, there is a point-to-point communication that is designed to be zoned. In the next section, the proposed protection strategy is presented.

IV. PROPOSED SUPPLEMENTARY PROTECTION SCHEME FOR MAS BASED HPS

To address the above-mentioned problems of conventional HPS, this paper presents a supplementary MAS based protection strategy. Using point-to-point communication, the proposed supplementary strategy is responsible for fault clearance in the primary layer of MAS, while in the case of network topology change or frequently change of network operating condition, the conventional MAS based strategy updates the protection settings using communication with higher levels of MAS. Since the proposed supplementary protection scheme does not need for operation of higher protection levels, it is also effective when a failure of the communication link between protection levels happens. The proposed scheme controls the effect of converter-based WTGs on the fault current in such a way that the coordination between protection devices is preserved.

In the conventional HPS, relay agents are at the lowest level of the hierarchical structure. These relays, which are of the overcurrent type in this paper, transmit the current information that they receive from the current transformer in the form of data values. This information is transmitted to the higher levels by using the IEC-61850 standard. The sample measured value (SMV) protocol allows the measured values to be transmitted in the network in a very short time. These relays only transmit the observed current changes to update their protection settings if required. This information is transmitted to the third level of protection, i.e., the central processing unit. By performing calculations at this level, the search table is updated and then, the appropriate settings are transferred to the lower level. In the second protection level, protection settings are sent to the relays for updating them. Relay agents update relays by receiving the new settings.

By adopting converter-based WTGs as the only agents of the supplementary protection, the proposed scheme aims to limit their influence on the distribution system protection. This scheme controls the produced power of WTGs using the communication links among them to preserve the protection coordination. If power production of the network in the presence of WTGs and its fault current in the case of no WTG are determined, the coordination time interval between the main and backup relays operations can be within the acceptable range by controlling the generated power of WTGs.

In the proposed method, the distribution network is divided into several zones. Depending on the importance of loads and required power quality, each zone consists of some WTGs. In this scheme, all WTGs are considered as agents capable of calculating their output powers and communicating with other agents. Before the first connection to the distribution network, an ID number is dedicated to each WTG. Using this ID number, each WTG can be controlled in its zone and in the case of communicating with other agents, the target agent can be determined. The ID number determines the identity of each WTG for other WTGs of its zone and that of other zones. Since each request is associated with an ID number, one WTG in each zone should be adopted as the master agent. The master agent manages the received requests and controls the produced power of WTGs with the same ID number. The presence of the master agent reduces the communication links and the cost related to the complex communication infrastructure. Also, by using this scheme, the management of zones is not dependent on a central controller, but the zones are managed by their master agents in a distributed form. Fig. 6 shows the implementation of the proposed scheme on the study system of Fig. 1. The main features of the master agent are WTG rating and its distance to the main relay of its zone. If one WTG has a higher rating and is closer to the main relay, it has a higher priority to be adopted as the master agent. Also, if the ratings of WTGs are the same, the closer WTG to the main relay is adopted as the master agent. They are due to the effect of WTG rating and location on the protection system coordination, as previously discussed in Section II. If the WTGs ratings and their distances to the main relay are the same, each WTG can be adopted as the master agent.

The study system includes WTG sets. Each WTG set consists of several parallel-connected WTGs. Regarding the network condition and relay settings, the master agent of each zone manages the produced power of WTGs.

To preserve CTI and to limit the influence of WTGs on the short circuit current, the master agent has the following tasks:

1) Communicating with master agents of other zones;
2) Monitoring the WTGs power productions;
3) Determining the fault zone; and
4) Managing the produced power of each zone by controlling the produced power of WTGs.

A. COMMUNICATING WITH MASTER AGENTS OF OTHER ZONES

To make a bidirectional communication between agents and to exchange data among them, a communication infrastructure should be made [37]. Regarding the capability of data transfer over a long distance, high bandwidth, and immunity to electromagnetic interference (EMI), a fiber optic-based communication infrastructure is a proper choice for making communication links among distributed agents of distribution network [51], [52]. The fiber optic modules should be installed in each agent to communicate with other agents. This paper employs the standard IEC 61850 to implement the communication links.

Each zone has one ID number; the agents of each zone use this ID number to communicate together. If a WTG is considered to be connected to the network, first, it should be registered with a specific ID number. All agents with the same ID number communicate together in their local zone. If the agents of a zone want to communicate with the agents of another zone, their request is performed by the master agent of their zone. For example, when the power production

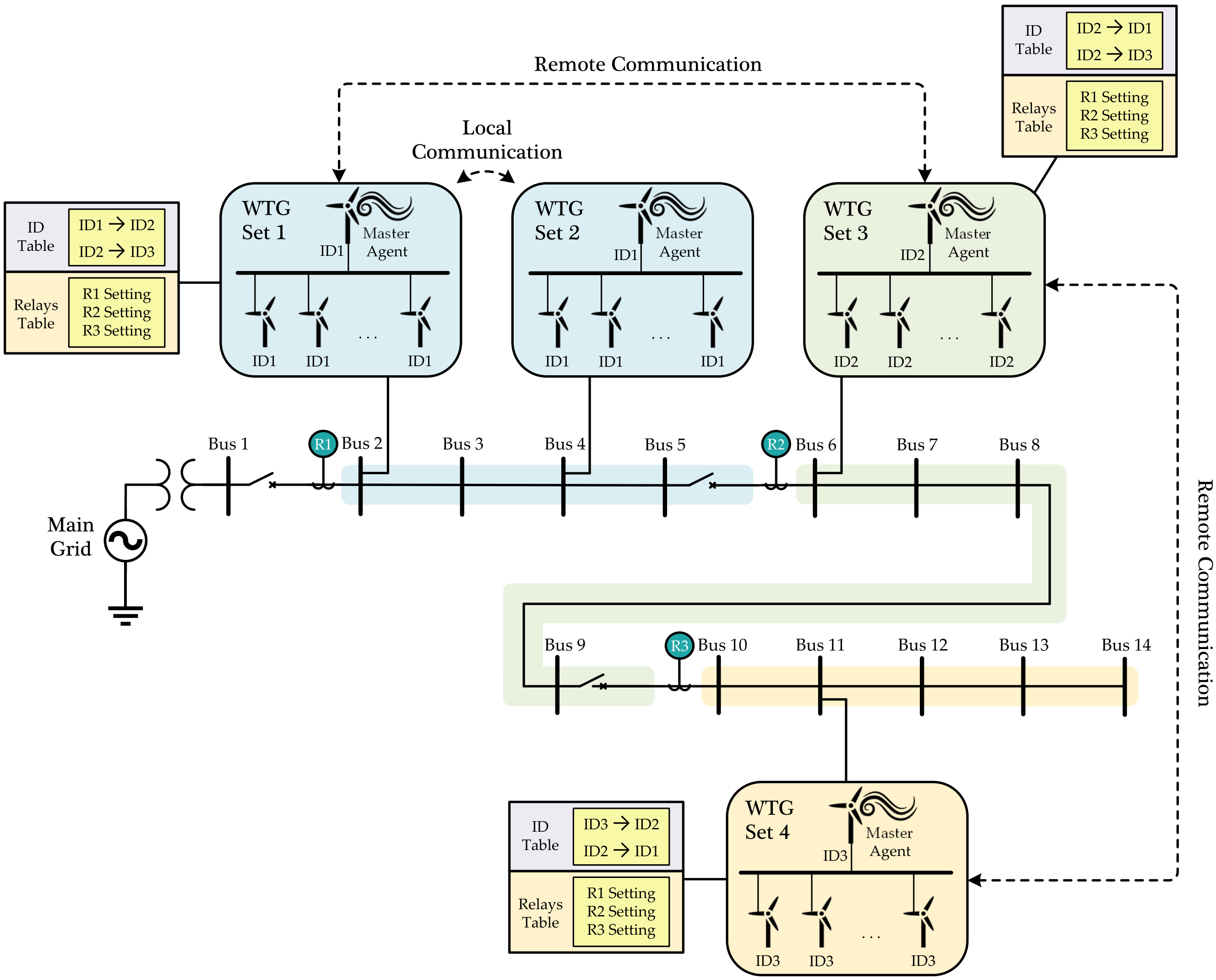


FIGURE 6. Implementation of the proposed supplementary protection scheme.

TABLE 2. Parameters of the study test system.

Short-circuit power of the main substation		430 MVA
Length of feeder F1		15 km
Length of feeder F2		11 km
Conductor	Type	Pirelli-AACSR/AC
	Size	120 mm^2
	Line shape	Horizontal - Headway type & not transposed - radial
	Legs altitude	9 m
Load	Total Demands	60 MW
	Transformer	20/0.4 kV – 1250 kVA – DYg

of zone 1 should be reduced for preserving the protection coordination, first, the master agent of this zone determines the amount of power reduction and sends the command to WTGs of its zone. If the power reduction of zone 1 is not allowed due to the presence of critical loads or this power reduction cannot preserve the protection coordination alone, the master agent of zone 1 sends the power reduction command to the master agent of its neighbor zone.

Each zone communicates with its neighbor zones and also sends the information of each neighbor zone to other neighbor zones (a point-to-point communication). Fig. 6 shows this type of communication between protection zones. Zone 2 sends the required data of zone 3 to zone 1 and vice versa. If the master agent of zone 1 wants to communicate with a non-neighbor agent, the data is transferred through the interface zone(s). An ID table is defined for each master agent

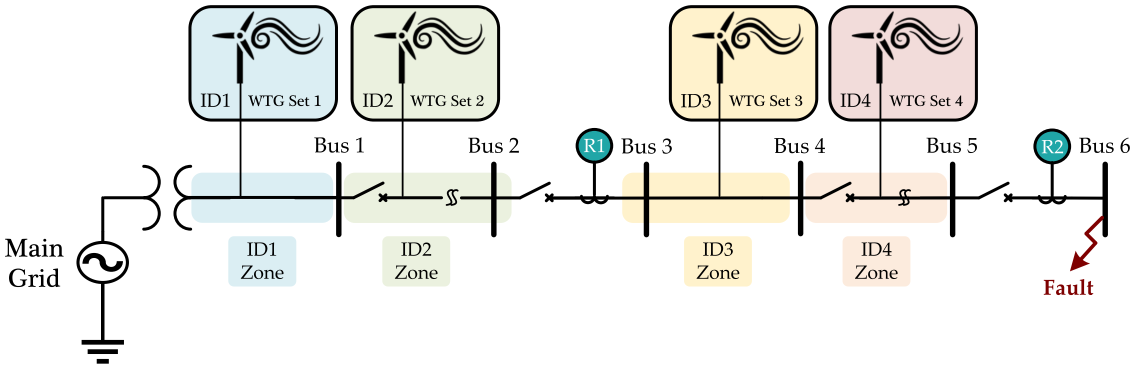


FIGURE 7. Various WTG locations in the distribution network.

TABLE 3. Information of ID zones.

ID Zone	Neighbor_Zones [ID number, Position]	Relays_Location [Relay, Position]	Relays_Setting	Local_Variables
ID1	[ID2,DS]	[R1,DS], [R2,DS]	[GSR1,$I_{f,max1}$], [GSR2,$I_{f,max2}$]	[P_1,I_1]
ID2	[ID1,US], [ID3,DS]	[R1,DS], [R2,DS]	[GSR1,$I_{f,max1}$], [GSR2,$I_{f,max2}$]	[P_2,I_2]
ID3	[ID2,US], [ID4,DS]	[R1,US], [R2,DS]	[GSR1,$I_{f,max1}$], [GSR2,$I_{f,max2}$]	[P_3,I_3]
ID4	[ID3,US]	[R1,US], [R2,DS]	[GSR1,$I_{f,max1}$], [GSR2,$I_{f,max2}$]	[P_4,I_4]

to send the information to the target zone. To make this table, each master agent should put the information of its neighbor agents in its ID table and share this table with the master agent of neighbor zones. The neighbor master agent also shares its ID table with that master agent and accordingly, these master agents update their ID tables. When a new zone with a new ID number is connected to the network, it sends a message to the neighbor zones to announce its connection and shares its ID table with the master agent of neighbor zones.

B. MONITORING THE WTG UNITS

In the conventional power systems, the network monitoring system is employed to increase the reliability and power quality and to control the power production and consumption [53]. In the proposed scheme, the master agent should monitor the produced power of WTGs of its zone and send this information to the neighboring zones. By controlling the produced power of WTGs, the master agent manages the power production of its zone. When a fault occurs, regarding the measured fault current, the master agent reduces the WTGs produced power so much that the protection coordination preserves. To do this, the master agent should have those current data that protection relays are coordinated based on them to determine the miscoordination condition.

C. DETERMINATION OF FAULT ZONE

In Fig. 7, two relays are coordinated based on $I_{f,max}$. Master agents have enough data to manage their operating zones. This information consists of produced power and injected current to the network, location of agents of other zones and their position with respect to the protection system as well as its settings. Accordingly, each ID zone is determined as

ID Zone:{Neighbor_Zones:[ID,Position],
Relays_Location:[R,Position], Relays_Setting:[GSR, $I_{f,max}$],
Local_Variables:[P, I]},

where Neighbor_Zones determines the position of each zone with respect to other zones; if a zone is located downstream, its position is registered as "DS" while if a zone is located upstream, its position is registered as "US". Relays_Location determines the position of protection system relay with respect to the DG location ("DS" for downstream and "US" for upstream). Relays_Setting consists of relays settings and their maximum fault currents. Local_Variables determine the produced power and injected current of each zone. Table 3 presents the data of ID zones for Fig. 7.

Regarding Table 3, all agents know the position of other agents and update their tables based on this information. This table and its data are kept by the master agent of each zone and they are shared with other zones. Based on this table, ID zones determine the fault zone as follows.

1) FIRST STEP: DETERMINATION OF ID ZONES POSITION

Regarding considered local and remote communications for DGs, their presence in the network and their position with respect to each other are determined during their installation. Accordingly, using the shared Neighbor_Zones data, agents can know the position of other zones. For example, during installation, the ID1 zone receives the location data of ID2 as a downstream zone. This table is completed using data from other zones and expressed as

ID1 Zone: {Neighbor_Zones: [ID2,DS],[ID3,DS],[ID4,DS]}.

2) SECOND STEP: POSITION OF PROTECTIVE RELAYS AND THEIR SETTINGS

When the position of ID zones is determined, the position of protective relays with respect to DGs is determined during DGs installation. The master agent of each zone has Relays_Location and Relays_Setting data. For example, during the installation of ID1 DGs, it is known that R1 and R2 relays are located downstream of ID1. Among its neighbors, each zone determines which zones have the same Relays_Location with itself. For example, ID1 and ID2 have the same positions with respect to network relays:

ID1 Zone: {Neighbor_Zones: [ID2,DS], Relays_Location:[R1,DS], [R2,DS]}
ID2 Zone: {Neighbor_Zones: [ID1,US], Relays_Location:[R1,DS], [R2,DS]}

When a fault occurs, these zones compare their injected currents to determine the fault zone.

3) THIRD STEP: COMPARISON OF LOCAL VARIABLES TO DETERMINE THE FAULT ZONE

According to Section 2 of the paper, the closer to the fault point, the higher is the injected current of DG. First, based on data received from the neighbors, each zone sorts the ID zones based on their injected currents. Accordingly, for each zone, one can write

1) Input: IDi for i = 1, . . . , k
2) Sort (IDi [Local_Variables]) #Arranged in ascending order

The second parameter to find the fault zone is the power rating of DGs of each zone. The more power rating, the higher is the injected fault current of DG. However, the distance of each DG to the fault point also affects its effect on the fault current. Since each zone has the settings of the protection system and the values of maximum fault current that the relays were coordinated based on them, it can know its effect on the fault current during the fault condition. To determine the fault zone, the ID zone currents are investigated as follows.

- If the zone with the highest fault current (hereafter referred to as IMAX zone) has the highest power rating, the fault zone is determined based on Local_Variables and Relays_Location data. Since the DGs with small distance to the fault inject significant fault currents, the zones with same Relays_Location should be determined and their injected currents are compared with other zones. For example, based on Fig. 7, ID zones 1 and 2 and ID zones 3 and 4 have the same Relays_Location. There are two conditions: (1) If the injected current of zones with the same Relays_Location of the IMAX zone is much less than the current of IMAX zone, the distance of IMAX zone to the fault is longer than them. Thus, the fault is closer to the downstream zones. (2) If the injected current of zones with same Relays_Location of the IMAX zone is close to the current of IMAX zone, the injected current of the zones with different Relays_Location of the IMAX zone should be investigated; if the injected current of these zones is close to the current of IMAX zone, the downstream zones are closer to the fault because they inject significant fault currents with lower power ratings with respect to upstream zones.
- If the IMAX zone has the smallest power rating, this zone is the closest zone to the fault and based on its Relays_Location, the protection zone related to the fault is determined and it also manages neighbor zones, if necessary.
- If the zone with the highest power rating injects the lowest fault current, this zone is far from the fault and the downstream zones determine the fault zone by comparing the injected current of ID zones with the same Relays_Location. Based on the injected current of these zones and by comparing the location of other ID zones located inside the same protection zone, the protection zone related to the fault is determined.

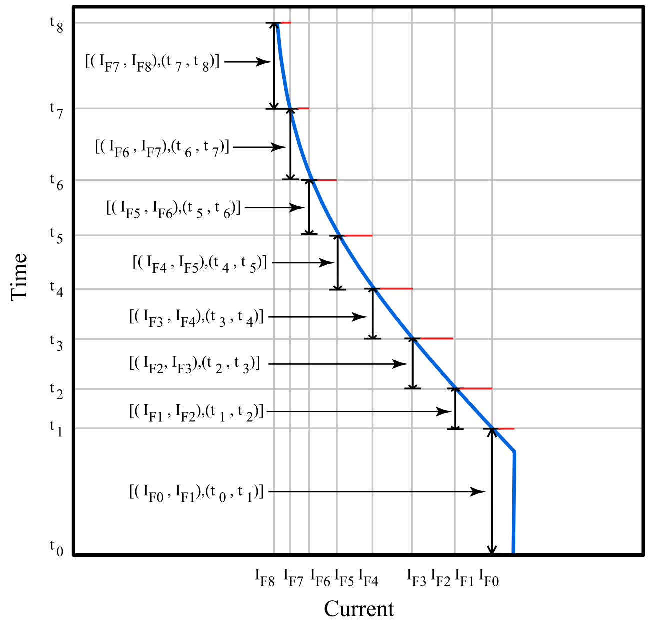


FIGURE 8. Timing of relay operation based on the fault current.

Thus, when a fault occurs, the performance of ID zones is compared with each other and by using the data of master agents, the protective relay covering the fault zone is determined. Then, those zones which have more effects on the performance of main and backup relays are managed to restore the protection coordination.

D. POWER MANAGEMENT OF ZONES

The power production of each zone is managed using its master agent by sending the command to other agents of that zone. If each zone wants to reduce its power production, its master agent sends the power reduction command to other

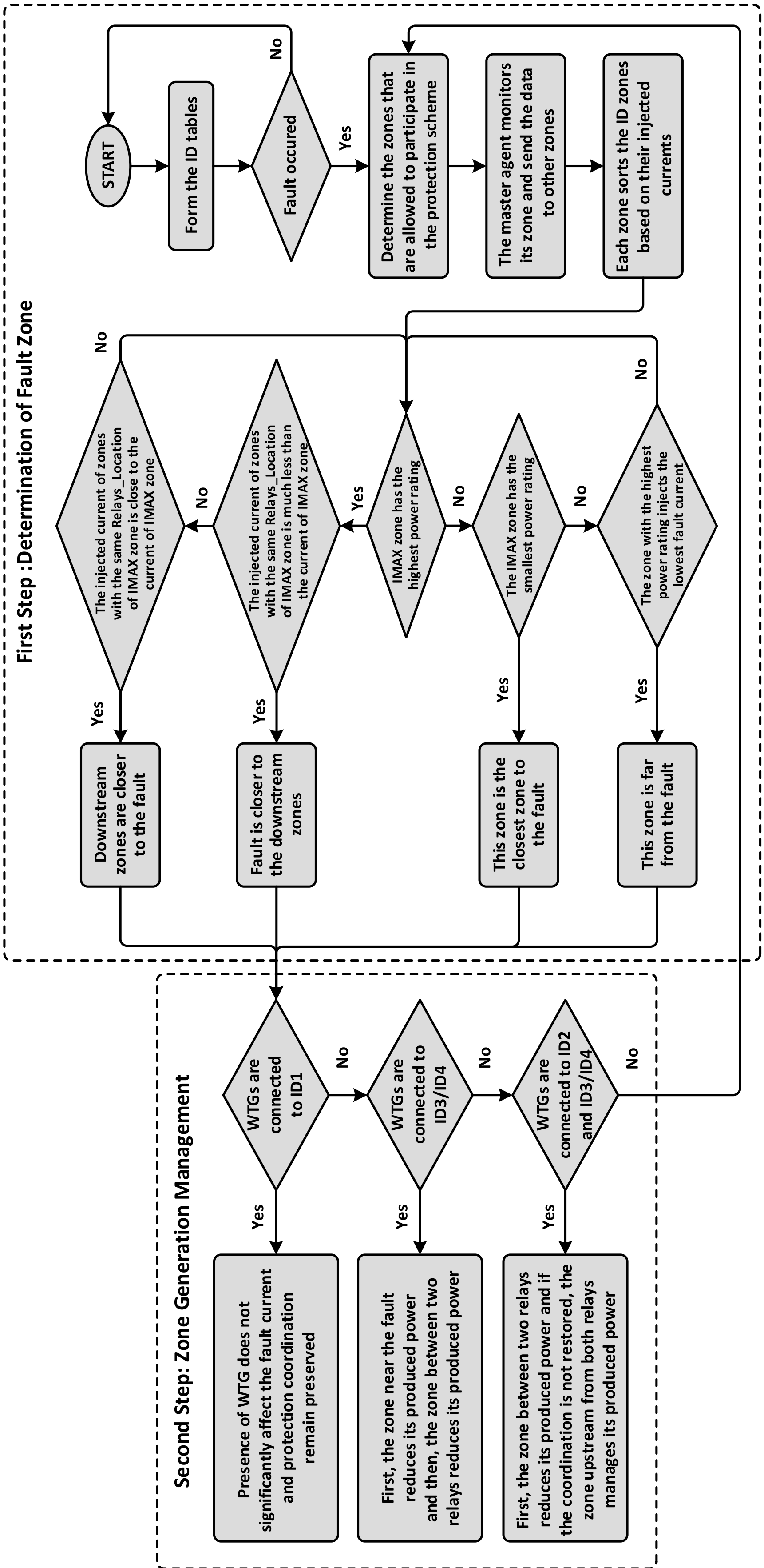


FIGURE 9. Flowchart of the proposed supplementary protection scheme.

agents of that zone. Depending on the received command, each master agent reduces the produced power of its WTGs.

DG agents have ID and relay settings tables. The latter table includes protection settings information. DG agents receive this information table and regarding they know conditions and locations of upstream and downstream protections, they manage the generated power of their zones. As shown in Fig. 8, DG agent has a lookup table inspired from the characteristic curve of the relay and it divides this curve based on the fault current and time information. Each section consists of relay current and operating time intervals. Proportional to injected current, DGs manage their generated powers.

Overcurrent relays are coordinated together for the maximum fault current in the absence of DGs. Thus, if the generated power of DGs of zones is managed so that the fault current backs to the coordinated interval, the protection coordination preserves. In Fig. 8, the characteristic curve of the overcurrent relay is divided into eight sections. Regarding each DG zone has these settings, it operates as follows.

1) Each zone knows the connection of other zones.
2) The master agent of each zone shares its generated power with other agents.
3) The master agent of each zone forms the following grouping for protections of its zone:

$$[(I_{F0}, I_{F1}), (t_0, t_1)] \ldots [(I_{F7}, I_{F8}), (t_7, t_8)]. \tag{6}$$

4) Based on the injected fault current, each zone has a lookup table. Using this table and based on a predefined program, the generated power of each zone is changed to restore the protection coordination. This table is determined based on the timing of relay operation and location of DGs with respect to relays locations.
5) The master agent of each zone, regarding produced power and output current of its zone and neighbor zones and predefined program, determines its generated power and if it is required, it sends the power production change command to neighbor zones and they change their generated powers according to the predefined program.

E. INCREASING THE RELIABILITY OF THE PROPOSED SCHEME

Regarding the important role of the master agent in controlling the power production of its zone during the fault condition, an alternative master agent should be adopted. If the main master agent fails, the alternative master agent performs its all functions. The alternative master agent should be one of the WTGs of that WTG set since they are similar in views of distance to main relay and rating. When the master agent substitution is required, the main master agent sends the ID table and relays settings to the alternative master agent.

F. OPERATING PRINCIPLE OF THE PROPOSED SUPPLEMENTARY PROTECTION SCHEME

Fig. 7 shows the various WTG locations in the distribution network. Regarding the results of Section II, the effect of WTGs on the fault current seen by the relays depends on the WTG location. The operating principle of the proposed scheme is divided into two steps: (1) determination of fault zone and (2) zone generation management. Fig. 9 shows the algorithm of the proposed scheme. In the first step, first, ID tables of agents of various zones with zone data are formed. Then, it is determined which zones are allowed to participate in the protection scheme. Each master agent monitors its zone and sends the data to other zones. Based on data received from the neighbors, each zone sorts the ID zones based on their injected currents. Then, the zone with the highest fault current (IMAX) is determined. If this zone has the highest power rating, the zones with the same Relays_Location are determined and by comparing their injected currents with IMAX, the zones that are close to the fault point are determined. If the zone with IMAX has the lowest power rating, this zone is the closest zone to the fault point. If the zone with the highest power rating injects the smallest fault current, this zone is far from the fault point. When the condition of zones are determined, the second step of the proposed scheme is started.

In the second step, WTG locations are categorized into four groups: (1) ID1 that is upstream from the main and backup relays and is far from the fault point, (2) ID2 that is upstream of both relays and is near the fault point, (3) ID3 that is between the main and backup relays and is far from the fault point, and (4) ID4 that is between both relays and is near the fault point.

- If WTGs only are connected to the ID1 zone, they do not significantly affect the current of relays since this zone is far from the fault.
- If WTGs are connected to the zones between the main and backup relays, they have the most effect on the protection miscoordination and the changes of relay currents, based on Section II. Therefore, these zones should reduce their power production. In this condition, first, the zone near the fault should reduce its production and if the coordination does not improve, the zone far from the fault reduces its generated power.
- If WTGs are connected to the ID2 and ID3/ID4 zones, first, the zones located between two relays control their produced power due to their more impact on the protection coordination and if the coordination does not improve, the zones upstream from both relays control their produced power.

V. PERFORMANCE EVALUATION

The performance of the proposed protection system is investigated for the study test system of Fig. 10 which is a section of the real distribution system of the Isfahan city in the center of Iran. The study test system is simulated in the ETAP environment. The 63/20 kV substation feeds two feeders F1 and F2. These feeders supply their loads independently. The loads are supplied by the 20/0.4 kV transformers. The overhead lines of the study test system are three-wire and four-wire in the 20 kV and 0.4 kV sections, respectively. The parameters of the study

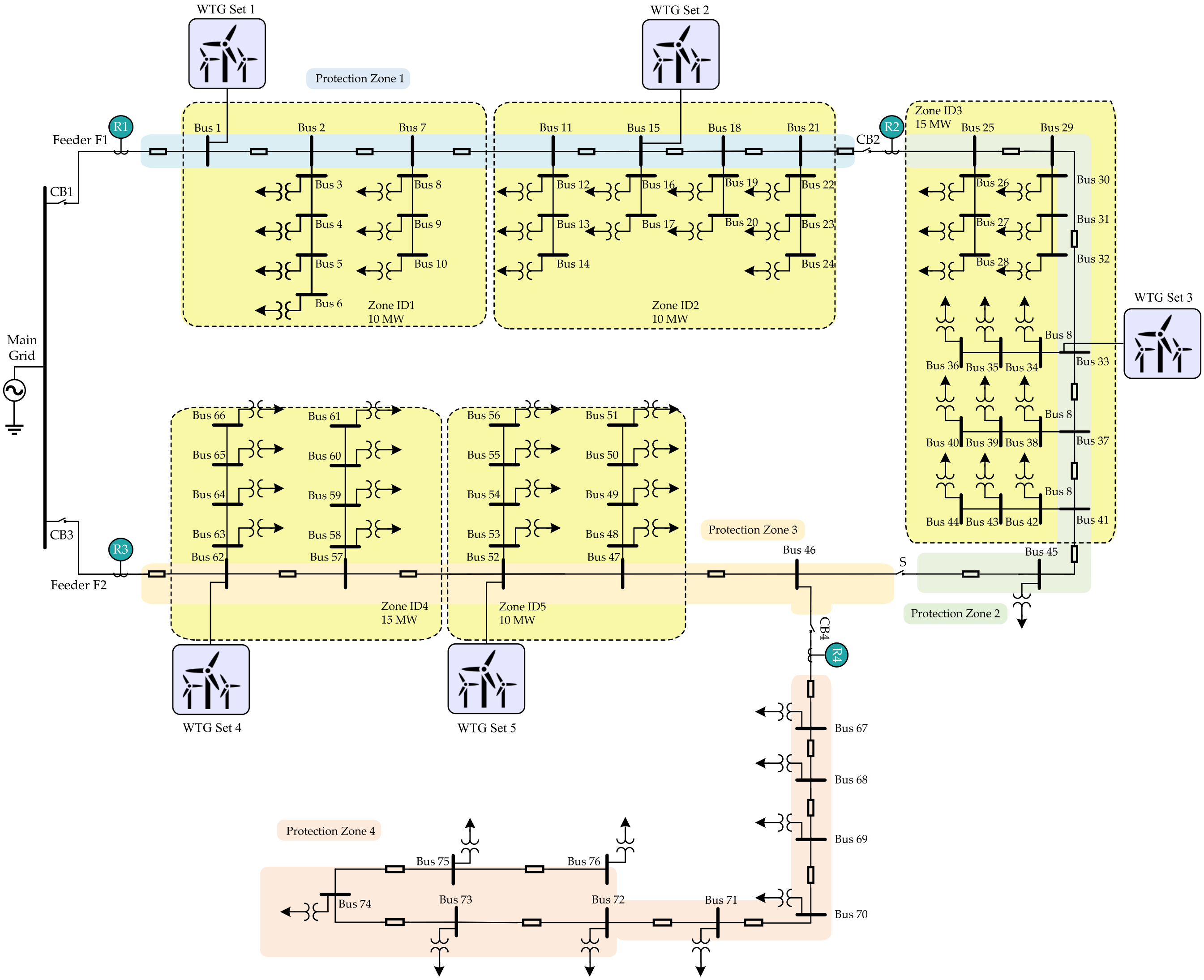


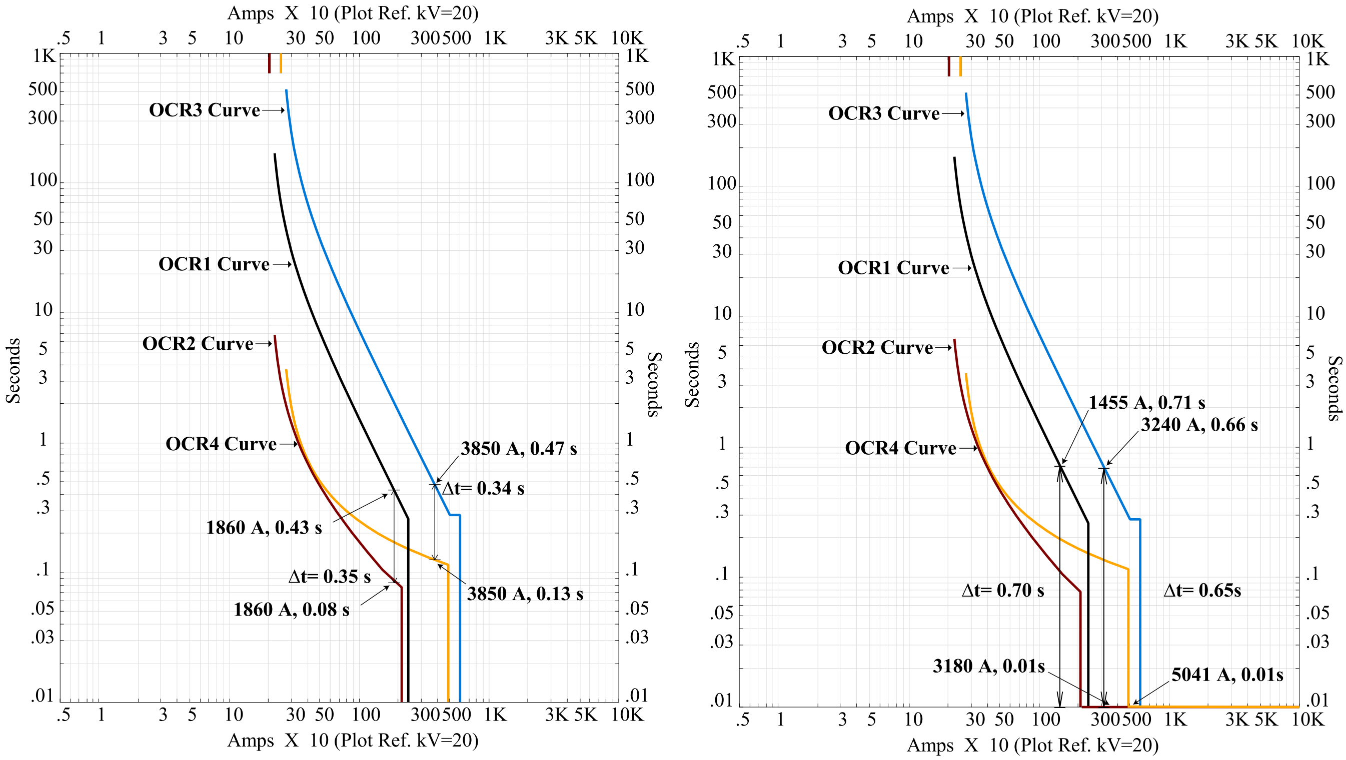
FIGURE 10. Study test system.

test system are presented in Table 2. This network consists of four main protection zones and continuous feeding of zone 3 loads is of great importance. To this end, F1 and F2 feeders are connected together using the switch S in such a way that loads of zone 3 are supplied through zone 1 or zone 3. There is an interlock between switch S and circuit breakers CB1 and CB3. If CB1 and CB3 are closed, the switch S is not closed to prevent the formation of a ring network. If the switch S is closed, one of the circuit breakers CB1 and CB3 are opened.

The protection devices arrangement is shown in Fig. 10. R1 and R2 are installed at F1 while R3 and R4 are installed at F2. When switch S is open, R1 is the backup relay of R2 while R3 is the backup relay of R4. When switch S is closed, all sections of the network are supplied by one feeder. In this condition, if CB3 is open and S is closed, R1, R2, and R4 protect the network and should be coordinately operated; R2 is the backup relay of R4 and R1 is the backup relay of R2. When CB1 is open and S is closed, the network is supplied by F2. In this condition, R2, R3, and R4 protect the network; R3 is the backup relay of both R2 and R4. Before the connection of full-scale converter-based WTGs to the study test network, there are several group settings for protection relays regarding the various operating conditions of the network. These settings should be loaded on the relays to clear the fault as fast as possible in the primary protection level. These group settings are presented in Table 4. Regarding the status of the network switches and change of protection zone of relays, the presence of WTGs in the network should be investigated in various operating conditions. Then, regarding the relay settings before the connection of WTGs, the proposed supplementary scheme preserves the protection coordination by limiting the influence of WTGs on the fault current.

TABLE 4. Group settings of protection relays before connection of WTGs.

Breaker State	S: open, CB1: closed, CB3: closed			S: closed, CB1: closed, CB3: open			S: closed, CB1: open, CB3: closed		
Relay No.	Curve Type	I_P (A)	TMS (s)	Curve Type	I_P (A)	TMS (s)	Curve Type	I_P (A)	TMS (s)
R1	Extremely inverse	1.36	0.44	Extremely inverse	1.09	1.1	No operation	–	–
R2	Very inverse	2.04	0.05	Very inverse	1.46	0.3	Very-inverse	1.6	0.16
R3	Extremely inverse	1.67	1.38	No operation	–	–	Long-inverse	1.09	0.05
R4	Inverse	3.34	0.05	Inverse	1.94	0.05	Very inverse	2.19	0.05



(a) (b)

FIGURE 11. Protection coordination between the relays operations when S is open. (a) no WTG in the study system and (b) in the presence of WTGs in the study network without using proposed scheme.

The study test system is divided into 5 zones; the zones ID1, ID2, and ID3 are in feeder 1 while ID4 and ID5 are in feeder 2. The produced powers of ID1 to ID5 are 10 MW, 10 MW, 15 MW, 15 MW, and 10 MW, respectively. Regarding the location of these zones, when WTGs are connected and the master agent is adopted, the ID table of each zone is formed based on the connected WTGs in that zone and its protection settings and it is shared with other zones. To evaluate the performance of the proposed supplementary scheme, three network topologies are studied as follows.

A. CASE 1: SWITCH S IS OPEN AND CB1 AND CB3 ARE CLOSED

When switch S is open and there is no WTG in the network, R1 with the characteristic curve of extremely inverse and R2 with the characteristic curve of very inverse protect feeder F1. Also, R3 with the characteristic curve of extremely inverse and R4 with the characteristic curve of inverse protect feeder F2. In this condition, the protection system coordinately operates. Fig. 11(a) shows this coordination when a fault occurs. But, when the WTGs are connected to the network, the existing protection settings are not proper and the coordination time interval between the operations of relays is not the proper value, as shown in Fig. 11(b).

Table 5 presents the ID table of each zone after sharing information among agents. First, all WTGs produce their rated power. When a fault with maximum fault current occurs in the main protection zone of R2, the fault current seen by this relay is 3180 A, which this increased current disrupts the relays coordination. To address this problem, the produced

TABLE 5. ID tables of master agents for the case 1.

ID1 Table	ID1 → ID2 ID2 → ID3 ID3 → ID5 ID5 → ID4	Relay Number TMS (s) Maximum Fault Current (A)	R1 0.44 5950	R2 0.05 1860	R3 1.38 12000	R4 0.05 3850	ID1: 10 MW ID2: 10 MW ID3: 15 MW ID4: 15 MW ID5: 10 MW
ID2 Table	ID2 → ID1 ID2 → ID3 ID3 → ID5 ID5 → ID4	Relay Number TMS (s) Maximum Fault Current (A)	R1 0.44 5950	R2 0.05 1860	R3 1.38 12000	R4 0.05 3850	ID1: 10 MW ID2: 10 MW ID3: 15 MW ID4: 15 MW ID5: 10 MW
ID3 Table	ID3 → ID2 ID2 → ID1 ID3 → ID5 ID5 → ID4	Relay Number TMS (s) Maximum Fault Current (A)	R1 0.44 5950	R2 0.05 1860	R3 1.38 12000	R4 0.05 3850	ID1: 10 MW ID2: 10 MW ID3: 15 MW ID4: 15 MW ID5: 10 MW
ID4 Table	ID4 → ID5 ID5 → ID3 ID3 → ID2 ID2 → ID1	Relay Number TMS (s) Maximum Fault Current (A)	R1 0.44 5950	R2 0.05 1860	R3 1.38 12000	R4 0.05 3850	ID1: 10 MW ID2: 10 MW ID3: 15 MW ID4: 15 MW ID5: 10 MW
ID5 Table	ID5 → ID4 ID5 → ID3 ID3 → ID2 ID2 → ID1	Relay Number TMS (s) Maximum Fault Current (A)	R1 0.44 5950	R2 0.05 1860	R3 1.38 12000	R4 0.05 3850	ID1: 10 MW ID2: 10 MW ID3: 15 MW ID4: 15 MW ID5: 10 MW

power should be controlled in such a way that the protection coordination is close to the no WTG condition. Regarding the simulation results and status of CB1 and CB3 during the fault, the injected current direction of WTGs is from the WTG location to the fault point. In this condition, each zone is informed about the location of its neighbor WTGs to know their power production and data. Since the fault occurs inside the protection zone of R2, ID1 and ID2 should reduce their generated power. Due to the long distance to the fault point, ID4 and ID5 do not significantly affect the protection coordination between R1 and R2. Thus, first, the master agent of zone 2 reduces its generated power to 2 MW due to the short distance to the fault. Then, as shown in Fig. 12, it sends a command to the master agent of zone 1 to reduce the generated power of this zone to 2 MW. Fig.13(a) shows the protection coordination between R1 and R2 in the new condition.

In the new operating condition, if a fault occurs inside the main protection zone of R4, due to the long distance of ID1 and ID2 zones to the fault point, the power production should be controlled by the ID4 and ID5 zones. In this case, the master agent of zone 5 reduces its generation to 5 MW and sends a command to the master agent of zone 4 for reduction of produced power of this zone to 5 MW, as shown in Fig. 12. The restored protection coordination between R3 and R4 is shown in Fig. 13(b).

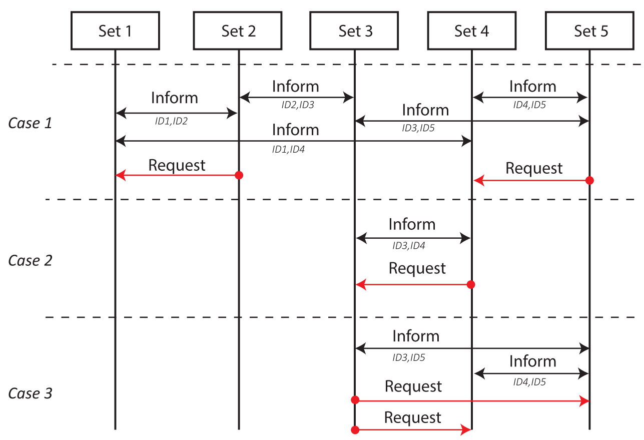


FIGURE 12. Event diagram showing communications among zones for studied scenarios.

B. CASE 2: SWITCH S AND CB1 ARE CLOSED WHILE CB3 IS OPEN

When switch S is closed and there is no WTG in the network, R1 with the characteristic curve of extremely inverse, R2 with the characteristic curve of very inverse, and R3 with the characteristic curve of inverse protect the feeder F1. If CB1 is closed and CB3 is open, R3 does not have any role in the protection system and R1, R2, and R4 protect the feeder. In this

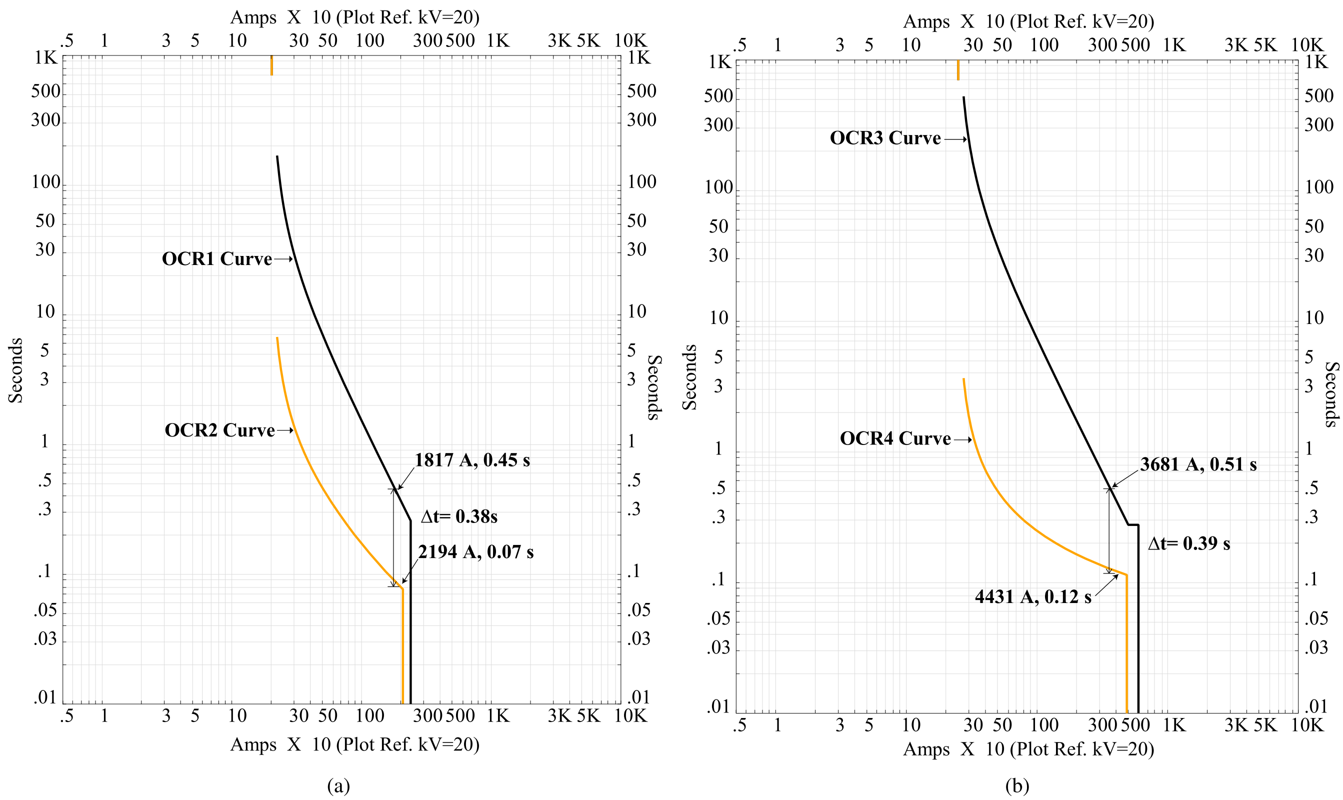


FIGURE 13. Protection coordination in the presence of WTGs in the network for the case 1. (a) between R1 and R2 and (b) between R3 and R4.

TABLE 6. ID tables of master agents for the case 2.

ID3 Table	ID3 → ID4	Relay Number	R1	R2	R4	ID3: 15 MW
		TMS (s)	1.1	0.3	0.05	ID4: 15 MW
		Maximum Fault Current (A)	5950	1860	1300	
ID4 Table	ID4 → ID3	Relay Number	R1	R2	R4	ID3: 15 MW
		TMS (s)	1.1	0.3	0.05	ID4: 15 MW
		Maximum Fault Current (A)	5950	1860	1300	

condition, R4 protects its protection zone. R2 should protect zone 3 as the main protection zone and also it should operate as the backup relay of R4. In this condition, the proper settings are set on the relays and they operate coordinately before the connection of WTGs, as shown in Fig. 14(a).

The relay settings are related to the condition of no WTG in the study system. Regarding the WTG location, this information is transmitted to relays to know the network protection settings. In this case, it is assumed that WTGs are connected to ID3 and ID4 zones only. Table 6 presents the agents' data. When WTGs are connected to the network, the short circuit levels of protection zones change. In this condition, the short circuit currents of the R2 and R4 zones are 1190 A and 4800 A, respectively. Due to the increment of fault currents in these zones, the produced power should be controlled in such a way that if R2 fails, R1 operates as the backup relay with proper CTI and if R4 fails, R2 operates with proper CTI. To do this, when a fault with maximum fault current occurs in the protection zone of R4, WTGs located near the fault point should reduce their produced power and far WTGs increase their power production. In this condition, WTGs are located between the main and backup relays. Thus, first, ID4 located near the fault reduces its generated power to 5 MW. Then, it sends a 5 MW power reduction command to the master agent of the ID3 zone, as shown in Fig. 12. Fig. 14(b) shows the protection coordination between R2 and R4 in the new condition.

C. CASE 3: SWITCH S AND CB3 ARE CLOSED WHILE CB1 IS OPEN

If switch S and CB3 are closed and CB1 is open, R1 does not any role in the protection system. When there is no WTG

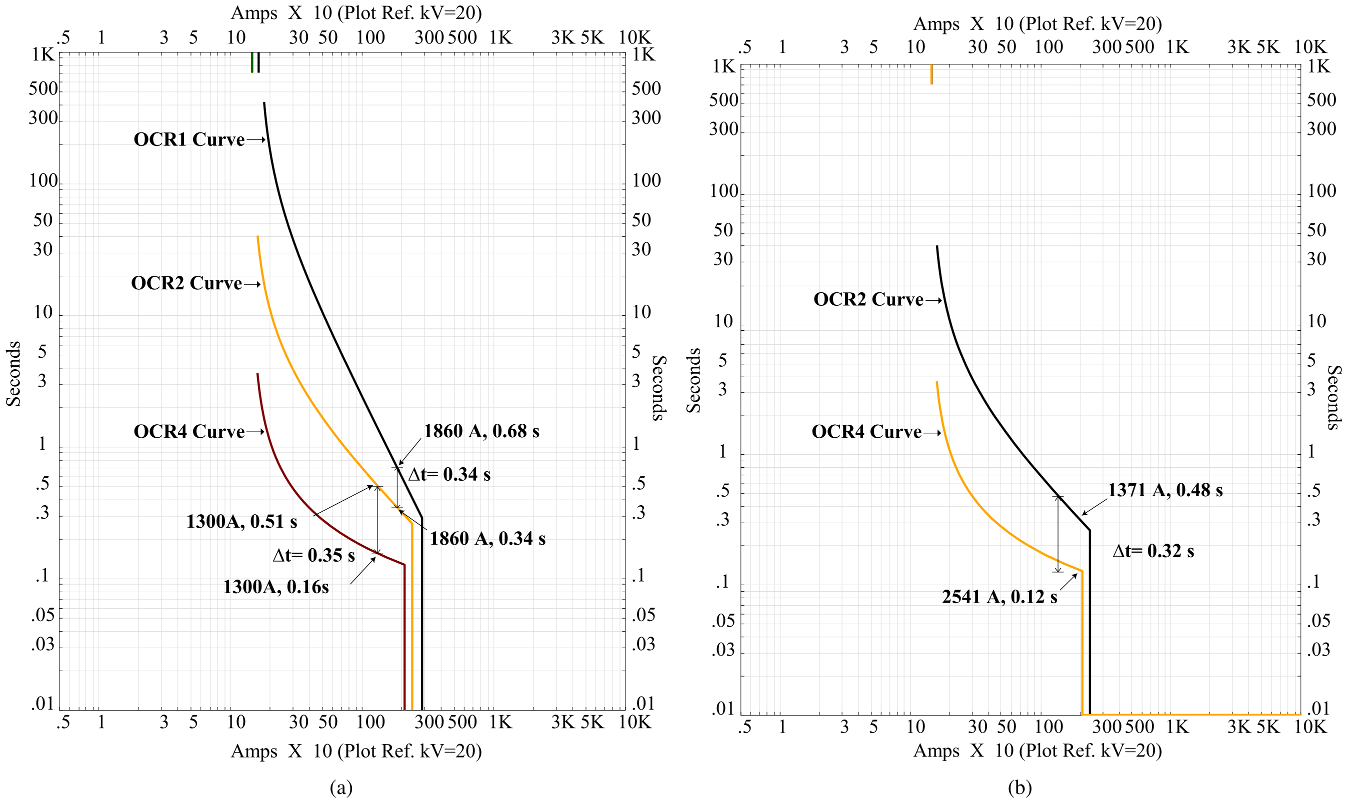


FIGURE 14. Protection coordination when S and CB1 are closed. (a) between the relays when WTGs are not connected to the study system and (b) between R2 and R4 in the presence of WTGs in the network.

TABLE 7. ID tables of master agents for the case 3.

ID3 Table	ID3 → ID5 ID5 → ID4	Relay Number	R2	R3	R4	ID3: 15 MW ID4: 15 MW ID5: 10 MW
		TMS (s)	0.16	0.05	0.05	
		Maximum Fault Current (A)	2040	12000	3850	
ID4 Table	ID4 → ID5 ID5 → ID3	Relay Number	R2	R3	R4	ID3: 15 MW ID4: 15 MW ID5: 10 MW
		TMS (s)	0.16	0.05	0.05	
		Maximum Fault Current (A)	2040	12000	3850	
ID5 Table	ID5 → ID4 ID5 → ID3	Relay Number	R2	R3	R4	ID3: 15 MW ID4: 15 MW ID5: 10 MW
		TMS (s)	0.16	0.05	0.05	
		Maximum Fault Current (A)	2040	12000	3850	

in the study system, R2 with the characteristic curve of very inverse, R3 with the characteristic curve of long inverse, and R4 with the characteristic curve of very inverse protect the feeder F2 coordinately. In this case, the operations of R2 and R4 are different from case 1 in that S is open. In this condition, R2 current direction changes and only zone 1 is its main protection zone. R3 should operate as the backup relay of both R2 and R4 protection zones. Fig. 15(a) shows the protection coordination between these three relays for the maximum fault currents.

In this case, it is assumed that WTGs are connected to ID3, ID4, and ID5 zones. These zones inform each other about their connection and share their data. These data are presented in Table 7. The relay settings are related to the condition of no WTG in the network. When WTGs are connected to the study system, the fault current of zone 1 protected by R2 is 2994 A while that of zone 4 protected by R4 is 7250 A. Thus, if a fault occurs inside the main protection zone of R2, the power production should be changed in such a way that protection coordination between R3 and R2

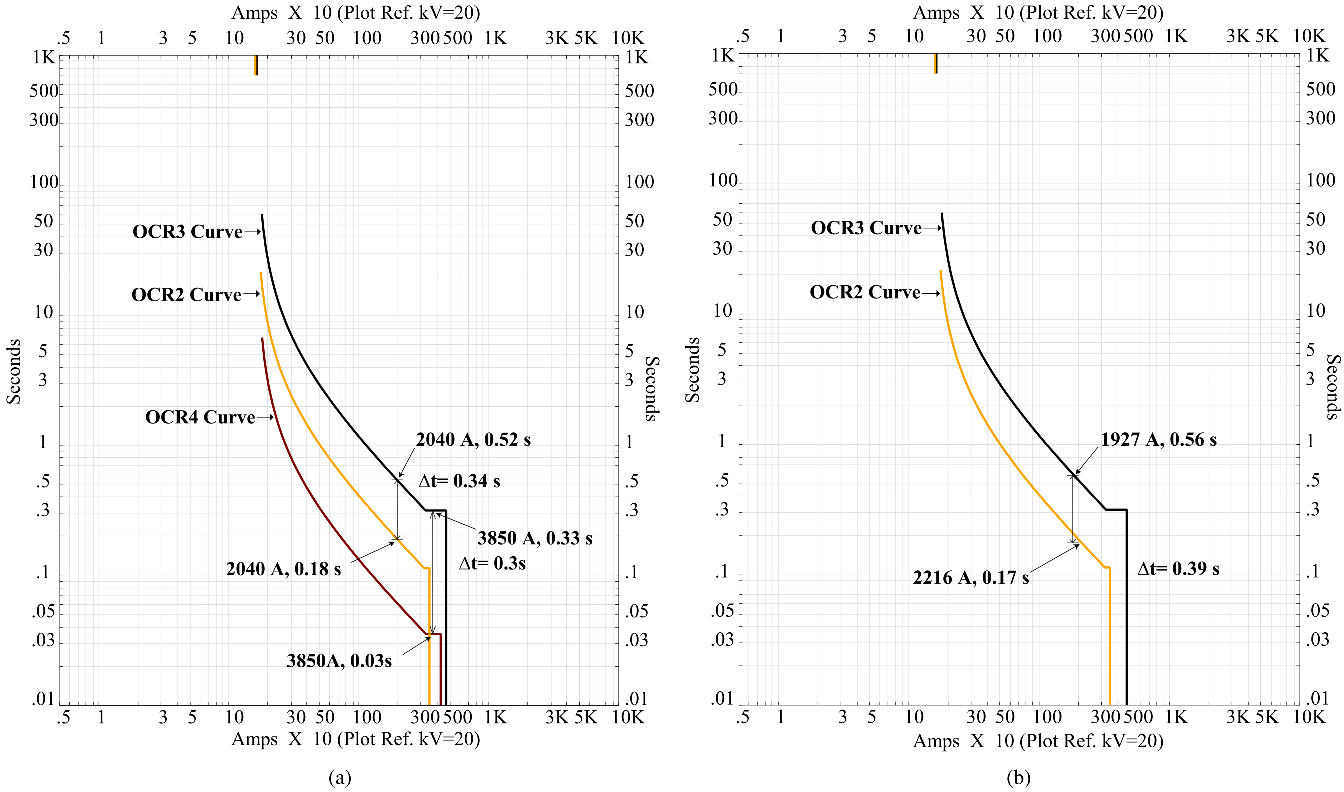


FIGURE 15. Protection coordination when S and CB3 are closed. (a) between the relays when WTGs are not connected to the study system and (b) between R2, R3, and R4 in the presence of WTGs in the network.

TABLE 8. Injected current of WTGs for all case studies.

	Case 1				Case 2		Case 3	
	Zone 2		Zone 4		Zone 4		Zone 2	
	Before	After	Before	After	Before	After	Before	After
WTG Set 1	398 A	98 A	72 A	82 A	–	–	–	–
WTG Set 2	1300 A	286 A	47 A	54 A	–	–	–	–
WTG Set 3	1890 A	1890 A	216 A	246 A	2300 A	880 A	1000 A	212 A
WTG Set 4	212 A	260 A	940 A	334 A	2000 A	812 A	381 A	82 A
WTG Set 5	132 A	163 A	980 A	532 A	–	–	373 A	112 A

still preserves. All three production zones are far from the fault point; due to the long distance to the fault point and the short distance to R3, ID4 and ID5 zones result in more reduction in R3 current and consequently more reduction of the relay operating speed. Thus, it is necessary to prevent the overcurrent of R2 by reducing the ID3 current. On the other hand, by decreasing the generated power of ID4 and ID5, the reduction of fault current seen by R3 should be avoided. First, ID3 should reduce its generated power to 2 MW. Then, as shown in Fig. 12, it sends the commands to ID4 and ID5 to reduce their produced power to 2 MW. Fig. 15(b) shows the protection coordination between R2 and R3 when the fault occurs inside the main protection zone of R2. The results show that CTI between main and backup relays is properly preserved.

The injected current of the WTGs for all case studies before and after fault management are presented in Table 8.

VI. DISCUSSION

The objective of this paper is to prevent protection miscoordination when a fault occurs during updating new settings calculated in conventional hierarchical MAS based protection system [31] on relays. The only proposed solution for this purpose is to use additional overcurrent relays besides the installed ones [31]. However, there are two main disadvantages to this solution from economical and protection speed points of view. Using additional relays increases the cost of the protection system while the proposed strategy uses the available potential of MAS based protection system and thus, it does need for extra equipment. Also, in the conventional

TABLE 9. Comparison between Proposed Protection Scheme and MAS based Protection Scheme Proposed in [31].

	[32]	Proposed
Relay Type	Directional Relays	Independent of relay type
Time duration of setting update	Several seconds	Zero
Time duration of central processing	Neglected	Zero (No control center)
Time delay of communication between levels	Neglected	Zero (No level)
Time duration of relays coordination check	40 ms	Zero
Need for relay settings update	Yes	No
Time duration of central controller communication with protective agents	44 ms	Zero (No control center)
Time duration of agents communication with central controller	28 ms	Zero (No control center)
Operating time of main relay	2100 ms	120 ms
Operating time of backup relay	3170 ms	510 ms

hierarchical MAS based protection system, the required time for updating relay settings t_{final} is calculated as

$$t_{final} = t_{send} + t_{cc} + t_{receive} + t_{upload}, \tag{7}$$

where t_{send} is the time duration of sending information to the control center by agents, t_{cc} is the time duration of processing information and calculations, $t_{receive}$ is the time duration of receiving the information and new settings, and t_{upload} is the time duration of uploading new information on the relays. As mentioned in [31], the final time can be significant. In the proposed strategy, due to no need for communicating with higher levels of MAS based hierarchical system, the time durations of sending and receiving information are zero. Also, it does not require a control center for protection system management. Thus, the final operating time of the proposed strategy is much lower than that of the conventional MAS based hierarchical system. A detailed comparison with the MAS based protection scheme proposed in [31] is presented in Table 9.

VII. CONCLUSION

This paper is motivated by the miscoordination of MAS based HPS due to time-consuming processes of collecting and analyzing the network information and of taking and transferring the proper decision. The proposed supplementary protection limits the influence of converter-based DGs on the protection system coordination of distribution networks by managing their produced powers. By dividing the network into several zones and transferring information among them using a distributed communication, the proposed scheme manages the fault current using the primary protection level of HPS. DGs are adopted as the only agents of the proposed scheme and each zone includes a master agent to manage its produced power. The operation of the proposed supplementary protection is independent of the control center of MAS based HPS and consequently, it is not susceptible to the failure of communication links between protection levels. Due to no need for communicating with higher levels of MAS based hierarchical system, the control center, and additional overcurrent relays, the proposed protection scheme is superior to the conventional MAS based protection system from both economical and protection speed points of view. The effectiveness of the proposed scheme is verified through both normal operation and network topology changes scenarios on the Isfahan distribution network. The proposed backup protection strategy can be implemented in future modern distribution systems with other types of electronically-interface DGs such as photovoltaic systems where the installed capacity of these units is so high to result in protection miscoordination. The development of the proposed supplementary protection scheme considering the grid code requirements and lateral protection can be considered as future works.

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