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Multi-agent based protection scheme using current-only directional overcurrent relays for looped/meshed distribution systems

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Abstract

The complexity of the design of the protection system using directional overcurrent relays, for modern power distribution systems has been increased due to the looped/meshed operation and the penetration of distributed generations. Finding a reliable and efficient protection scheme that can be easily implemented in these distribution systems is a major challenge. An efficient solution could be the use of artificial intelligent-based multi-agent systems. This paper proposes a novel distributed intelligent based multi-agent protection scheme, which makes use of current-only directional over current relays as agents for detecting and locating faults and isolating faulty areas (lines/busbars) in the distribution systems. All agents can make on-board decisions by exchanging binary data, and do not need a control centre, so the safety of the protection system against one-point failures and cyber-attacks is increased. The proposed scheme does not need to exchange analogue data, and, therefore, it prevents the high bandwidth communication links. Moreover, it is free from the traditional coordination between relays. This scheme is implemented on the IEEE-14 bus and IEEE-30 bus test systems with the distributed generations and several scenarios have been simulated to evaluate its performance.

1 | INTRODUCTION

Today, most of the distribution systems are operated in a meshed/looped manner to increase the reliability of the system and provide uninterruptible power supply. On the other hand, if a fault occurs in the power system, the faulty area must be immediately identified and isolated from the network so that the network equipment is not damaged and the rest of the healthy areas of the network can continue to operate. Therefore, the power systems require an appropriate and reliable protection scheme for accurate detection and localization of faults and rapid clearance of faults. The necessity for the use of directional overcurrent relays (DOCRs) as an economical protection device to protect the system against bidirectional fault currents instead of using distance and differential relays is a major challenge in the meshed/looped and interconnected distribution systems. Therefore, the use of advanced technology and intelligent algorithms has become of paramount importance for the proper design of the protection system in these networks [1].

In these years, different techniques have been proposed for detection and location of faults in the distribution systems. These techniques use different methods that can be separated in two main categories; namely, into conventional and knowledge-based methods. The former includes impedance-based and traveling wave-based methods, while the latter includes expert systems (ES), fuzzy logic (FL), artificial neural networks (ANN), genetic algorithm (GA), support vector machines (SVM), matching data approach and hybrid methods [2]. In [3], the residual voltage has been used to detect the high impedance faults in the distribution systems with connection of DGs. In [4] the major problem with iterative approaches has been addressed, and to overcome these problems, a petri net approach has been suggested. These methods use data that can be obtained from smart devices, such as; phasor measurement units (PMUs) and protection devices [5]. In [6], a fuzzy inference...
system (FIS) has been used to develop the fault detector and classifier of high impedance faults (HIFs) on the radial distribution system. For this purpose, the fundamental current components of each phase are used to detect and classify the shunt faults. In [7], a hybrid technique is proposed for fault detection. In this method, the stationary wavelet transform (SWT) filter has been used to reduce data to improve the computational time. Then the reduced data are used to train ANN and SVM for fault detection and classification. In [8], a data-driven strategy has been proposed to detect faults and identify their locations based on the multi-level governance regionalization and quantification of the fault detection results in the distribution systems with distributed energy resource (DER). In this strategy, a general criterion has been presented to divide the distribution systems into several subregions based on the division of the network tree to help the hierarchical search for the location of faults. It combines support vector data description (SVDD) and kernel density estimation (KDE) to find quantified trust criterion for the fault detection in each subregion according to their p-values. In [9], a fault identification (FI) algorithm is proposed based on Tellegen’s theorem for identifying faults in the unbalanced active distribution networks (ADNs). This approach uses voltage and current phasor information obtained from the PMUs, located at the ends of divided zones of the distribution network. The phasor data are sent to a central control centre (CCC) to identify the faulty feeders using the proposed FI method.

To overcome the disadvantages of past works related to complex mathematical methods and centralized approaches and in order to enhance the reliability, availability and service quality of power systems, several automatic algorithms have been proposed based on multi-agent systems (MAS) to detect, localize and isolate faults [10]. MAS can be considered as a new and potential technology to solve problems of management and operation of modern power systems. Recently, MAS has been applied in various fields of power engineering such as; condition monitoring, post-fault diagnosis, protection system, active distribution systems operation, power system restoration and microgrid control [11]. A careful research on the capabilities and benefits of MAS show that it is a suitable and efficient technology for the use in complex and interconnected distribution systems. For protecting such systems, centralized, decentralized and distributed architecture by means of MAS can be used [12].

In [13], a self-healing algorithm based on multi-agent systems has been presented for the fault location, isolation and service restoration (FLISR) in the distribution systems with DGs. The structure of the proposed algorithm has two layers of zone and feeder agents. The role of zone agents in the first layer is to implement control actions for building a restoration plan by interacting with other zone agents. In addition, the role of feeder agents in the second layer is to implement the protection algorithm by exchanging data together to identify the fault location and send trip signals to proper circuit breakers (CBs) to isolate the faulty area. A new protection scheme using agents has been proposed for distribution systems in [14], in which the agents interact with each other by exchanging their local information. It also provides an effective backup protection coordination through information exchange between agents to reduce the fault clearance time. For fault location, line isolation, and service restoration in the distribution systems, an approach has been proposed in [15], which combines impedance-based fault location method and MAS. In [16], an MAS-based protection scheme is presented to maintain the protective coordination between the overcurrent relays (OCRs) in the distribution network in the presence of DGs. This scheme has been implemented in two separate levels. The first level includes relay agents, which act as the main protection by interacting together, and the second level includes DG agents that perform the backup role, when the first level protection is not effective. The authors in [17], present a distributed protection system based on MAS for fault localization, isolation and restoration of MGs. The fault location is determined by using agents and by calculating the phase angle difference of the measured currents by the PMUs located on both ends of the distribution lines. In [18], a protection scheme based on MAS is presented for a looped microgrid (MG), which is independent of a CCC. In this work, OCRs are considered agents and token-based communication of IEC 61850 is used within relays to prevent any conflict in their operation to work properly in both radial and looped MGs.

The previous protection schemes have weaknesses that can be summarized as follows:

The mathematical methods cannot be used in common protection devices, because they have high computational burden and require high investment to implement and are not suitable for the distribution systems. In most of these, coordination between relays is based on time-current characteristics, while the relay’s settings complexity is high, and there is a possibility for loss of coordination. Theoretically, MAS-based centralized, decentralized and distributed architecture for protection schemes provide similar results, but the distributed approach has more advantages and better efficiency than others, which can be found in Table 1 [17, 19, 20].

On the other hand, lack of metering sensors is the main problem for the distribution systems in protection systems issues.

### Table 1: Comparison of MAS architectures

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Cent.*</th>
<th>Decent.**</th>
<th>Dist.***</th>
</tr>
</thead>
<tbody>
<tr>
<td>Require to CCC</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Amount of required data</td>
<td>Huge</td>
<td>Little</td>
<td>Mean</td>
</tr>
<tr>
<td>Decision-making speed</td>
<td>Slow</td>
<td>Fast</td>
<td>Faster</td>
</tr>
<tr>
<td>Computational burden</td>
<td>Heavy</td>
<td>Mean</td>
<td>Light</td>
</tr>
<tr>
<td>Communication capacity</td>
<td>High</td>
<td>Mean</td>
<td>Low</td>
</tr>
<tr>
<td>One-point failure risk</td>
<td>High</td>
<td>Mean</td>
<td>Low</td>
</tr>
<tr>
<td>Cyber-attacks risk</td>
<td>High</td>
<td>Mean</td>
<td>Low</td>
</tr>
<tr>
<td>Scalability</td>
<td>Low</td>
<td>Mean</td>
<td>High</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Low</td>
<td>High</td>
<td>Mean</td>
</tr>
<tr>
<td>Reliability</td>
<td>Low</td>
<td>Mean</td>
<td>High</td>
</tr>
<tr>
<td>Expansion</td>
<td>Hard</td>
<td>Easy</td>
<td>Mean</td>
</tr>
</tbody>
</table>

*Centralized, **Decentralized, ***Distributed.
Therefore, the trend is toward developing fault detection and location algorithms based on finite sensors.

Despite improvements in the protection schemes, achieving the fast operation, easy and low cost design, and scalability is the main concern.

Accordingly, this paper presents an applicable and low cost protection scheme to detect and identify the location of faults and isolate faulty areas (lines/busbars) in the meshed/looped distribution systems based on the distributed MAS that only uses current-only DOCRs as agents.

The main benefits of the proposed scheme are:

- The proposed scheme is applicable and low cost, because it uses the current-only DOCRs as agents without requiring voltage transformers.
- The proposed technique is based on fully distributed MAS and all agents have the on-board decision making capability without requiring CCC, therefore the speed of decision making and reliability of the protection system is increased and the potency and efficacy of the scheme is enhanced against one-point failure and cyber-attacks.
- The proposed protection scheme is designed based on exchanging binary signals of fault direction detection sign between agents, not requiring analogue data exchange. This means that the bandwidth requirements of communication networks are reduced, which lead to minimizing communication delays to detect and isolate faults, and reduce the cost of the scheme.
- The proposed scheme has a novel backup protection system, not requiring traditional coordination between the primary and backup relays; hence, it reduces the complexity of the protection scheme and improves the selectivity; and operational speed.

The proposed scheme is tested using different case studies on the developed IEEE 14-bus and IEEE 30-bus standard distribution system with the connection of DGs and, it is compared with the optimum relay setting using conventional standard distribution system with the connection of DGs and, it is compared with the optimum relay setting using conventional DOCR and adaptive DOCR obtained in [21]. The modelling and simulation of electrical parts is done in MATLAB/Simulink. Since MATLAB could not provide a tool to set up an agent framework, the Java Agent Development Environment (JADE) platform based on Foundation for Intelligent Physical Agents (FIPA), is used to implement the proposed MAS-based protection system. In order to control and make decisions by MAS, it is essential that there be a real-time interconnection between JADE and MATLAB/Simulink to exchange data. MACSimJX (Multi-Agent Control for Simulink program) is an interface that provides the needed real-time interconnection between MATLAB/Simulink and JADE, according to Figure 1 [22].

The rest of the paper is presented as follows: In Section II, the problem statement is presented, Section III briefly introduces the current-only DOCR. Section IV describes the proposed MAS based protection system. The performance evaluation and attained results are shown in Section V. Conclusions are presented in Section VI.

2 | PROBLEM STATEMENT

Overcurrent relays are used as primary protection for radial distribution systems. In order to increase the security and selectivity of the protection system, the looped/meshed topology or parallel lines in the distribution systems require DOCR to detect the direction of the fault current. The fault direction is binary data that indicate whether the fault is in the front or back of the relay [23]. Apart from that, the backup protection relays are usually used to complete the protection scheme and they should be coordinated with the corresponding primary relay. The settings and coordination between the protection relays, need to analyse the critical operational conditions and short circuit for all power system operational conditions, which is a complex and time consuming task. In addition, determining the optimal settings for all conditions of power system operation is also difficult [12]. Moreover, conventional DOCRs use the phase-angle difference between the fault current and the reference voltage to estimate the fault direction. Therefore, it is necessary to use both voltage transformers (VTs) and current transformers (CTs). This makes directional relaying more expensive than non-directional relaying. Therefore, unlike transmission systems, non-directional relaying is often used in the distribution systems [24]. Hence, the trend is toward using cheaper utility like the current-based directional relaying in the distribution systems.

To address the drawback mentioned in the above and have an intelligent, low cost, simple and reliable protection scheme without requiring the complex task of protection coordination between relays, by referring to the advantages of distributed MAS, this work will focus on the application of MAS using current-only DOCRs for fault detection and isolation of faulty areas (lines/busbars) in the looped/meshed distribution systems. The main idea is that any numerical relays installed at the end of lines in the meshed/looped distribution systems could be an intelligent agent that is able to process data and makes decisions to detect and localize faults by exchanging information and interacting with neighbouring agents. Moreover, agents are able to isolate the faulty areas by sending the trip signal to relevant CBs.
The operational principles of directional relay only based on current is introduced in [25]. Other researchers have proposed different methods to identify fault direction in the distribution systems by using this principle. In [26], a current-only directional relaying algorithm has been introduced without using pre-fault current that increases the speed and accuracy of digital relay. Therefore, in this work, this algorithm is used with a few changes to detect the faults direction as briefly described below.

Figure 2 shows the single-line diagram (SLD) of the system used to explain the fault direction detection algorithm only based on current. During-fault current, which is measured using S-transform technique in the relay, is used to estimate the forward and reverse of fault current direction by considering the power flow direction. It is noteworthy that in this algorithm, there is no need to use pre-fault current. In this figure, \( I_{FF} \) and \( I_{FR} \) are forward fault current phasor and reverse fault current phasor, respectively. Apart from that, \( Z_{SEF} \) is impedance between the source and the forward fault point and \( Z_{GFR} \) is impedance between the grid and the reverse fault point, which can be expressed as follows:

\[
Z_{SEF} = |Z_{SEF}| \angle \theta_1 \tag{1}
\]

\[
Z_{GFR} = |Z_{GFR}| \angle \theta_2 \tag{2}
\]

The proposed reference phasor to detect the direction of fault current is calculated as follows:

\[
I_{ref} = |I_{FF}| \angle \frac{Z_{SEF} \angle \theta_1}{2} = |I_{FR}| \angle \left( \theta_2 + \frac{\pi}{2} \right) \tag{3}
\]

\[
I_{ref} = |I_{FR}| \angle \frac{Z_{GFR} \angle \theta_2}{2} = |I_{FF}| \angle \left( \theta_1 - \theta_2 - \frac{\pi}{2} \right) \tag{4}
\]

3.1 Forward power flow state

In this case, we assume the power flow direction of the power system is in the forward direction (from source to grid). The fault location may be on the forward or backward side of the relay.

3.1.1 Forward fault condition

According to Figure 2, in this condition, the faulty point is located in the forward side of the relay and the power flow direction is the same as the fault current direction of relay. The during-fault current phasor in this condition is given by

\[
I_{during\_fault} = I_{FF} = \frac{|V_s| \angle \delta}{|Z_{SEF}|} = |I_{FF}| \angle (\delta - \theta_1) \tag{5}
\]

The negative of \( I_{FF} \) is expressed as

\[-I_{FF} = |I_{FF}| \angle (\delta - \theta_1 + \pi) \tag{6}\]

Now a new reference current phasor \( I_{ref} \), which is used to detect the direction of the fault current is defined as

\[
I_{ref} = |I_{FF}| \angle \frac{Z_{SEF} \angle \theta_1 - Z_{GFR} \angle \theta_2}{2} = |I_{FR}| \angle \left( \theta_2 + \frac{\pi}{2} \right) \tag{7}
\]

3.1.2 Reverse fault condition

Suppose a fault occurs at the backward side of the relay when the power flow direction is the same as the relay current direction. The during-fault current phasor in this condition can be expressed as

\[
I_{during\_fault} = I_{FR} = \frac{|V_s| \angle 0}{|Z_{GFR}|} = |I_{FR}| \angle (-\theta_2 + \pi) \tag{8}
\]

The negative of \( I_{FR} \) is expressed as

\[-I_{FR} = |I_{FR}| \angle (-\theta_2 + \pi + \pi) = |I_{FR}| \angle (-\theta_2) \tag{9}
\]

In this condition, the reference current phasor \( I_{ref} \) can be expressed as

\[
I_{ref} = |I_{FR}| \angle \frac{Z_{GFR} \angle \theta_2 - Z_{SEF} \angle \theta_1}{2} = |I_{FR}| \angle \left( -\theta_2 + \frac{\pi}{2} \right) \tag{10}
\]

Now, the new direction detector (DD) is defined as

\[
DD = \angle I_{ref} - \angle I_{during\_fault} \tag{11}
\]

By substituting the Equations (3) and (5) in Equation (9), the result of DD for forward fault condition is obtained as

\[
DD_{forward} = + \frac{\pi}{2} \tag{12}
\]

By substituting the Equations (6) and (8) in Equation (9), the result of DD for reverse fault condition is obtained as

\[
DD_{reverse} = - \frac{\pi}{2} \tag{13}
\]

According to Equations (10) and (11), there is a \( \pi \) rad difference between the DD in the forward and reverse fault condition.
Despite this phase-angle difference, DD can be a proper criterion for identifying the forward and backward faults relative to relay. Therefore, if the DD is \((\frac{\pi}{2})^{rad}\), the fault is forward or if it is \((-\frac{3\pi}{2})^{rad}\), the fault is reversed.

The phasor location of forward and reverse fault condition in forward power flow state, is shown in Figure 3. It can be seen that the during-fault current phasor in reverse fault condition \((I_{FR})\) is in the opposite direction of the during-fault current phasor in forward fault condition \((I_{FF})\) and it has almost 180\(^\circ\) phase difference. However, the reference current's phasor is close to the source voltage phasor. Since the phase difference between the source voltage phasor and the grid voltage phasor is small, thus, it is possible to determine the fault current direction with respect to during-fault current without requiring pre-fault current and any bus voltage.

3.2 Reverse power flow state

In this state, the power flow is in the reverse direction (from grid to source). Similar to the above formulation, as proven in [26], the DD is not affected by the power flow direction of the power system, thus the criterion of fault direction detection for the forward power flow state is valid for the reverse power flow state, too.

3.3 Three-phase fault direction detection method

The computational algorithm presented in [26] has a separate calculation for each phase and will impose a large computational burden on the digital relays; it will also be reducing the speed of relay operation. According the proposed technique in [23], to extend the above algorithm for three-phase systems and for all types of faults, positive-sequence component instant of S-Transform is used in order to estimate during-fault current phasor to compute DD, because the positive sequence is available for all types of faults. Figure 4 shows the flowchart of the proposed fault current direction detection algorithm only based on current for all types of faults in the distribution systems.

4 PROPOSED MAS-BASED PROTECTION SCHEME

4.1 Multi-agent systems technology

An agent is a software (or hardware) component that is autonomous, social, reactive, and proactive. An agent entity is located in an environment that is autonomously able to react in response to its environment changes and cooperates with other agents in order to achieve a defined objective. The environment may be physical or computational that can be observable through sensors, program invocation, system calls, and messaging [11].

An MAS is a distributed system consisting of multiple agents that can model complex systems and provide feasibility to achieve the common or conflicting goals for agents. Agents require the ability to communicate with users, system resources, and each other agents. The interaction with other agents is supported by an agent communication language (ACL) and special protocol, which allows agents to converse and negotiate rather than simply exchange information. The job and tasks of agents is defined in the agents’ behaviour. The characteristics and applications of MAS in power engineering are presented in [11].

4.2 MAS-based protection system architecture

In this section, a new distributed architecture of protection scheme is presented based on MAS for the distribution system. The aim of this paper is to propose a distributed protection scheme based on MAS with simple implementation, low
complexation and light cost. Therefore, in the proposed architecture, the numerical DOCRs, which are geographically distributed in the distribution system, and are considered agents. The numerical DOCRs are known as intelligent electronic devices (IEDs), which have the basic characteristics and features such as I/O interface, communications and decision making capability to support a software agent. The agents take the necessary information such as local measurement current and circuit breaker (CB) status from the environment (distribution system) or other agents, then process data, and, according to their tasks, perform proper actions such as sending trip request messages to other agents and trip signals to relevant CBs.

Figure 5 illustrates the distributed MAS-based protection scheme architecture. The proposed protection scheme consists of only protection relay agents (PRAs) for simple implementation, reduced cost and complexity. Each line includes the relays and CBs at both line-end considered as an area. All proposed agents communicate with each other not only within the same area, but also within different areas based on IEC 61850 protocol; thus the information could be exchanged between agents and areas. Since, this protocol provides convenient peer-to-peer communication between decentralized IEDs and speeds the critical time of exchange information (around 0.25 cycle) to meet the safety requirements of protection function in the power systems, it is suitable for the practical implementation [27].

4.2.1 Role of protection relay agent (PRA)

The structure of PRA is shown in Figure 6. The PRA requires the information of the system to make decisions. \( I_M \) is a current measurement by CT. CB\text{\textsubscript{Status}}, represents CB status which is a binary input into PRA from corresponding CB. Each PRA obtains relevant additional information by communicating with other PRAs. Each PRA makes a trip/non-trip signal decision by processing obtained data and interacting with the relevant other PRAs. Each PRA sends a trip signal immediately to corresponding CB, when fault occurs in its protection zone.

4.3 Fault direction detection algorithm

When the input current of an overcurrent relay exceeds a pre-set threshold, it operates and its internal logic activates the control outputs. This is to protect the power system against all types of short circuit. Usually, the RMS value of current fed from the CTs is used to compare with the pre-set pickup value. The fault occurrence is detected according to the below relation by the PRA.

\[
F_3 = \begin{cases} 
0; & 0 < I_M < I_P \quad \text{(No Fault)} \\
1; & I_P < I_M < \infty \quad \text{(Fault)}
\end{cases}
\]

where \( F_3 \) is the fault status, \( I_M \) depicts the RMS value of the current measurement at the relay and \( I_P \) shows the pickup current value of relay. To maintain the sensitivity of relay, the usual setting of \( I_P \) is between 1.5 to 2 time the nominal line load current passing through the relay in general conditions (\( I_{max}^{load} \)) and (half of) the minimum fault current it can observe (\( I_{min}^{fault} \)) [28], that can be written as

\[
I_{max}^{load} < I_P < 0.5 \times I_{min}^{fault}
\]

When each PRA detects a fault in the system, it immediately begins to calculate the direction of the fault current according to the flowchart in Figure 4. Depending on the fault status, fault direction and location, PRAs will produce a proper control signal and send it to the corresponding CBs. The required control signal (\( T_i \)) can be written as

\[
T_i = \begin{cases} 
1; & \left( \text{Keep close the CB} \right) \\
0; & \left( \text{Open the CB} \right)
\end{cases}
\]
4.4 | Fault localization method

This section refers to the method for identifying faulty areas of the distribution system.

4.4.1 | Fault localization method on the line

Basically, when a fault occurs on a line in the power system, one of the two line-end relays senses a change in the current direction relative to the direction of pre-fault current, while the other relay does not detect any change of current direction. Thus, the change in the current direction could be used as a symptom for identifying the faulty line [29]. In order to design both line and bus protection schemes, the forward direction is considered a direction that the relays should see to its line fault clearing. Therefore, the forward direction of line-end relay is defined towards the line, and its reverse direction is defined towards the bus. Thus, when a fault occurs on a line, the peer relays of this line see the fault current in the forward direction, while the adjacent relays of the relays will see this fault current in their reverse direction. The relays at both ends of a line are defined as the peer relays, which have the task of primary protection for their area fault clearing. The adjacent relays are those that have a common bus, which has the task of primary protection for their bus fault clearing, and each of them is the backup relay for the failure of its own adjacent relay and corresponding circuit breaker failure (CBF) of this relay. It is noteworthy that the forward and backward directions for each relay can be defined by changing the polarity of its associated CT.

In order to make a decision, in case of forward direction consider the fault direction sign as 1 (FDS = 1), in case of reverse direction as −1 (FDS = −1) and in the normal condition or no current state as 0 (FDS = 0). In the proposed method based on MAS, the faulty line is identified by exchanging the information of fault current direction detection by the two PRAs located at both line-ends. Each PRA in the line-end detects the fault current direction as flowchart in Figure 4. If the FDS of both PRAs in the line-end (peer PRAs) is 1, or FDS of one of them is 1 and that of the other is 0 (the second case is observed when the line is in the radial operation), the line is identified as faulty. If the FDS of PRAs in the line-end is opposite, the line is identified as fault-free, but one or more faults have occurred in another area of the power system. This procedure would increase the selectivity of the protection system. For any PRA located at a line-end, the decision making logic for fault localization on the line could be defined as in Table 2.

<table>
<thead>
<tr>
<th>Event</th>
<th>FDS of PRA</th>
<th>FDS of PRA’s peer</th>
</tr>
</thead>
<tbody>
<tr>
<td>No fault</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>The line is faulty</td>
<td>+1</td>
<td>+1</td>
</tr>
<tr>
<td></td>
<td>+1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>+1</td>
</tr>
<tr>
<td>Fault is outside of the line</td>
<td>+1</td>
<td>−1</td>
</tr>
<tr>
<td></td>
<td>−1</td>
<td>+1</td>
</tr>
</tbody>
</table>

4.4.2 | Fault localization method on the bus (busbar protection)

According to the forward and reverse direction defined for the relays in the above, when a fault occurs on a bus, all relays on this bus will see the fault current in their reverse direction. Thus, the decision-making logic for each PRA in terms of fault detection on its bus can be defined as follows.

In the proposed protection scheme based on MAS, the faulty bus is identified by exchanging the information of FDS by the adjacent PRAs. If the FDS of all adjacent PRAs is −1 or the FDS of one or more of them is −1 and the others are 0 (the second case is observed when the one or more lines connected on this bus is in the radial operation), the bus is identified as faulty. For any PRA, the decision making logic for fault localization on the bus can be defined as in Table 3.

<table>
<thead>
<tr>
<th>Event</th>
<th>FDS of a PRA</th>
<th>FDS of one adjacent PRA</th>
<th>FDS of others adjacent PRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>No fault</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>The bus is faulty</td>
<td>−1</td>
<td>0 or −1</td>
<td>0 or −1</td>
</tr>
<tr>
<td></td>
<td>0 or −1</td>
<td>−1</td>
<td>0 or −1</td>
</tr>
<tr>
<td></td>
<td>0 or −1</td>
<td>0 or −1</td>
<td>−1</td>
</tr>
<tr>
<td>Fault is outside of the bus</td>
<td>+1</td>
<td>0 or −1</td>
<td>0 or −1</td>
</tr>
<tr>
<td></td>
<td>0 or −1</td>
<td>+1</td>
<td>0 or −1</td>
</tr>
<tr>
<td></td>
<td>0 or −1</td>
<td>0 or −1</td>
<td>+1</td>
</tr>
</tbody>
</table>

4.5 | Backup protection scheme

The failure of a relay or its corresponding circuit breaker failure (CBF), is supported by the operation of the selected backup relays after a certain time delay, which is recognized as coordination time interval (CTI).

In the proposed protection scheme based on MAS, the relay failure and CBF backup protection is defined as follows:

4.5.1 | Relay failure backup protection scheme

In this paper, the adjacent relays of each relay are selected as backup relays for this relay. When a fault occurs on the line, the peer PRAs of this line see the fault current in forward direction (FDS = 1), while the adjacent PRAs of this peer PRAs see the fault current in reverse direction (FDS = −1), and at the same
time, they start their individual timer. If after the expiration of the set time (CTI), the FDS of all adjacent PRAs of a PRA persists as $-1$ and no signal is received from this PRA, they will assume that this PRA has failed to operate, thus they decide to operate as backup relay, for supporting this PRA. In this case they send a trip signal to their corresponding CBs to completely isolate the faulty line.

4.5.2 CBF backup protection scheme

CBF protection is a type of backup protection in the power systems. If a CB has failed and cannot isolate its faulty line, it is necessary that the adjacent CBs be opened for clearing the fault. Thus, in the conventional protection schemes, when the relay sends a trip command to a CB, it starts a timer at the same time. If the CB has not opened and the fault current persists after the timer has expired, the relay sends another trip command by hard wiring to open all adjacent CBs. In the proposed protection scheme based on MAS, the CBF backup protection technique is basically the same, except that it is performed by sending trip request messages. When a circuit breaker is failed, in case of fault detection on the line, the PRA sends a trip request message to all its adjacent PRAs to open their corresponding CBs, but in case of fault detection on the bus, the PRA sends the trip request message to its peer PRA to open its own corresponding CB.

4.6 The proposed protection scheme

The flowchart of the proposed protection scheme is illustrated in Figure 7.

At first, all PRAs registered their names and services to AMS agent, and DF agent respectively, in the JADE platform. Each PRA lists all PRAs, then identifies its peer PRA and adjacent PRAs. After that, each PRA constantly takes measurement current from corresponding CT, monitors its own CB status and sends it to all PRAs. The PRAs will detect the fault current according to the pickup setting when a changing situation like fault happens in the power system. It should be noted that, in this proposed scheme only pickup setting of relays is necessary and does not need the usual setting and coordination between relays. However, the traditional settings and coordination of relays can be used as a redundant protection system for MAS failure or communication failure in any area. When each PRA detects the fault, it immediately calculates FDS according to the algorithm shown in Figure 4, and sends it to its peer PRA and adjacent PRAs. Each PRA compares its FDS with that of its peer PRA and its adjacent PRAs, then makes fault location decisions according to logic shown in Tables 2 and 3. If a fault is detected on a line or bus, each PRA of this area sends a trip signal to open the corresponding CB, and will wait for the corresponding CB to open. If the fault current and the close status of CB persists after the defined time (CTI) (i.e. CB has failed), the CBF backup protection function of this PRA will act. So, in case of fault detection on the line, the PRA sends a trip request message to all its adjacent PRAs to open their corresponding CBs, but in case of fault detection on the bus, the PRA sends the trip request message to its peer PRA to open its own corresponding CB.

5 PERFORMANCE EVALUATION AND RESULTS

5.1 Test distribution systems

In order to evaluate the performance of the proposed protection scheme, the 33 kV section of IEEE 14-bus standard power distribution system is considered. The SLD of this system is shown in Figure 8. This looped/meshed distribution system is fed from the upstream network by two transformers (60 MVA, 132/33 kV) at buses 1 and 2; one compensator is also
connected to bus 1 [30]. This system is developed with DG units of rated 2 MVA, which is connected to bus 5 to 7 according data of [21]. In this work, all end-lines of this system and the end-line of DGs at the point of connection to the bus of the distribution system have been equipped with current-only DOCRs. The forward direction of these DOCRs is shown with an arrow. The characteristics of these relays are considered instantaneous time, and it only needs to set the pickup current value. Also, CTI is assumed to be 0.3 s. It is noteworthy that; each DGs would have its special protection system at the point of common coupling. Similarly, additional scenarios are tested based on the 33 kV section of IEEE 30-bus distribution network [30]. This system is developed with two DG units of rated 5 and 18 MVA, which are connected to bus 5 and 9 respectively. The single-line diagram of this system is shown in Figure 9.

5.2 | Simulation and results in IEEE 14-bus system

5.2.1 | Three phase short circuit fault

In this case, a three phase (LLL) fault type is applied in F13 at 0.1 s.

When the fault current is evident, as seen in Figure 10(a,b), PRA11 and PRA12 detect forward fault current direction (FDS = +1) at \( t = 0.121 \) s. At the same time, they exchange their FDS together and thereby they identify the fault in their area (F13). Then, they immediately produce the control signal 0 (trip signal) to open the corresponding CBs (i.e. CB11 and CB12), while other PRAs produce control signal 1, therefore the other CBs remain closed. As seen in Figure 11(a,b), PRA11 and PRA12 send trip signals at \( t = 0.125 \) s to open the CB11 and CB12 respectively. As shown in Figure 12(a,b), the faulty line is correctly identified and isolated in the shortest time (\( t = 0.132 \) s).

According Figure 13(a,b), it can be seen that the adjacent agents of PRA11 (PRA8) and PRA12 (PRA2) did not act because they identified the external fault.

5.2.2 | Circuit breaker failure (CBF)

In this case, the proposed CBF backup protection is analysed. Note that the timer is set to 0.3 s. For this purpose, a three

![Image of Circuit Breaker Failure (CBF)](image-url)
phase to ground (LLL-G) fault type is applied at $t = 0.1$ s in F11: assuming that CB13 fails and it cannot interrupt the fault current. According to Figures 14 and 15, it can be seen that PRA13 and PRA14 identify the fault in their area at $t = 0.122$ s and send control signal 0 at 0.125 s to open the corresponding CBs, (i.e. CB13 and CB14 respectively), and at the same time start their timers. Figure 16(a,b) shows the status of CB13 and CB14 after fault occurrence. As seen as, CB14 has opened while the CB13 has not opened after the 0.3 s has expired. Therefore, as shown in Figure 17(b), the fault current is still flowing through CB13. Thus, PRA13 sends a trip request message to all its adjacent agents (i.e. PRA4, PRA17) to open their relevant CBs. As shown in Figure 18(a,b), the PRA4 and PRA17 send trip signal at $t = 0.435$ s to open their relevant CBs (i.e. CB4 and CB17 respectively) after receiving the trip request the message from PRA13. Figure 19(a,b) illustrates that CB4 and CB17 (i.e. the adjacent CBs of CB13) had opened in $t = 0.46$ s and the faulty line was completely isolated from the network (see Figure 20(a,b)).

5.2.3 Busbar protection (BBP)

In this case, performance of the proposed busbar protection scheme is evaluated.

For this purpose, a phase to ground (L-G) fault type is applied at $t = 0.1$ s in Bus6. When the fault current is evident, as seen in Figure 21, all PRAs in this bus (PRA6, PRA14, PRA15 and PRA18) detect reverse fault current direction (FDS $= -1$) at close to $t = 0.122$ s. At the same time, they exchange their FDS together and thereby they identify the fault in their busbar. Then, they immediately send trip signal to open the corresponding CBs (i.e. CB6, CB14, CB15 and CB18) at $t = 0.125$ s (see Figure 22). As shown in Figure 23, the faulty busbar is correctly identified and isolated in the shortest time.
5.3 Simulation and results in IEEE 30-bus system

5.3.1 Multiple short-circuit faults

In this case, performance of the proposed protection scheme in clearing different types of faults which occur simultaneously in multiple different locations of the distribution system is evaluated.

In order to, a two phase to ground (LL-G) fault type is applied at $t = 0.1$ s in F17 (Fault-1), at the same time an L-G fault type is applied in F25 (Fault-2). According to the proposed scheme, relays R4, R21 and R23 are peer relays in F25, thus when a fault occurs on this line, they must be operating.

Figures 24–29 illustrate the simulation results of this case. As seen in Figure 24(a,b), the forward fault current direction (FDS = +1) is detected by PRA6 at $t = 0.122$ s and it is detected by PRA9 at $t = 0.125$ s. Thereby, they identify a fault (Fault-1) that occurs in their area, then they produce the control signal 0 at $t = 0.1233$ s and $t = 0.1267$ s to open the corresponding CBs, i.e. CB1 and CB2 respectively (see Figures 25 and 26). According to Figure 27, the peers PRA4, PRA21 and PRA23 detect forward fault current direction (FDS = +1) at $t = 0.1225$ s, $t = 0.121$ s and $t = 0.1285$ s respectively too. Thereby, they identify the occurrence of a fault (Fault-2) in their area (F25). Then, they produce the control signal 0 at $t = 0.1233$ s, $t = 0.1233$ s...
The results show the proposed protection scheme can detect and clear various types of faults, occurring simultaneously in the system.

5.3.2 Fault localization in radially operation condition of lines

In this case, performance of the proposed protection scheme in localization and clearing of fault on lines which operate in radial condition is evaluated.

For this purpose, assume CB2 had already opened, and the feeder 3-5-6-8 is operated in radial condition, in this case, an LLL-G fault type with fault resistance of 2 $\Omega$, is applied at $t = 0.1$ s in F22. When the fault current is evident, as seen in Figure 30(a,b), PRA19 detects forward fault current direction (FDS = +1) at $t = 0.131$ s and PRA2 does not detect fault current direction (FDS = 0), because the feeder is operated as radially. Therefore, according to decision making logic shown in Table 2, PRA19 identify the fault in its area, then sends trip signal at $t = 0.1333$ s to open the corresponding CB, i.e. CB19 (see Figure 31(a)). As shown in Figure 31(b), the faulty line is correctly identified and isolated in the shortest time ($t = 0.142$ s).

As can be seen from Figure 32, the adjacent agent of PRA19 (PRA18) does not act, because it has identified the external fault.

5.4 Comparison of relays operating time

In this section, operation times of the primary and backup relays in the proposed protection scheme is compared with the
TABLE 4  Relays operating times for different relaying approaches on IEEE 14-bus system with DGs on buses 5 and 7

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<td>p</td>
<td>b1</td>
<td>b2</td>
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<td>F8</td>
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<td>R4:</td>
<td>R6:</td>
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<td>R2:</td>
<td>R11:</td>
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<tr>
<td>Total</td>
<td>29.09</td>
<td>44.96</td>
<td>22.62</td>
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<tr>
<td>Overall relay operation time</td>
<td>96.67</td>
<td>41.98</td>
<td>—</td>
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<tr>
<td>Operation time reduction of MAS-based in comparison with conventional DOCR</td>
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<tr>
<td>Operation time reduction of MAS-based in comparison with ADOCR</td>
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</table>
Also, it can be seen that, the overall operation times in the conventional DOCR and ADOCR approaches are 96.67 and 41.98 s, respectively. Whereas overall operation times in the MAS-based protection scheme is 7.55 s, which is extremely reduced.

6 CONCLUSION

This paper proposes a distributed MAS-based protection scheme for looped/meshed distribution systems using current-only DOCRs. Details of the proposed MAS-based protection scheme for detecting, locating and isolating the faulty areas were presented. The proposed protection scheme includes line and busbar protection and it has the backup protection for relays and circuit breaker failures. This scheme only uses the current-only DOCRs as agents; therefore, investment on voltage transformers for directional relaying can be saved, which could be of high importance for the distribution systems. The protection scheme works in a distributed manner. No central management system is used to control and make decisions, so efficacy of the protection system is enhanced against one-point failure and cyber-attacks. It does not need to exchange analogue data, and, therefore, it prevents the high bandwidth communication links. The data exchange between agents and their interactions, increase the security and selectivity of the protection scheme, decrease the fault clearance time, and mitigate the malfunction of relays. Several faulty scenarios were simulated to evaluate the performance of the proposed scheme. The results confirm the proper operation of the proposed protection system and demonstrate its advantages. In this work, changes in the network topology due to operational conditions of DGs have not been considered in to account. This, worthwhile to be studied in our future works on the MAS-based adaptive settings for DOCRs in the distribution systems.

REFERENCES


