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Adaptive Protection in Smart Distribution Networks: Coordination Demonstration of Multi-Agent Systems

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***Abstract*—Modern protection relays play a critical role in ensuring the safety and reliability of electrical networks. These relays offer advanced communication capabilities for easy integration with other grid devices and enable remote monitoring and control. Integrating Multi-Agent Systems (MAS) has the potential to further enhance coordination and cooperation among relays distributed across the grid infrastructure, facilitating efficient monitoring, control, and decision-making processes. This article presents a practical implementation of an adaptive MAS-based protection approach for power grid coordination. By leveraging advanced multi-core processors, the implementation demonstrates the feasibility and effectiveness of MAS techniques in real-time data analysis, decision-making, and agent coordination. STM32MPU boards are programmed to emulate MAS-based protection relays, utilizing IEC 61850 GOOSE communication between them. The demonstration results showcase the ability of modern protection relays to enhance grid management through effective coordination among multiple relays.**

***Index Terms*—multi agent system, protection coordination, protection relay, IEC 61850**

I. INTRODUCTION

Modern protection relays are designed with a wide range of features to address the evolving needs of the power industry. One notable feature is the ability to perform multi-functional tasks, combining features such as over-current protection, differential protection, and voltage regulation within a single device. This consolidation simplifies the protection system, reduces costs, and improves system performance. Furthermore, state-of-the-art protection relays provide extensive communication abilities, facilitating remote monitoring and control while enabling smooth integration with other grid devices. In order to achieve efficient communication and interoperability, protection relays employ various protocols and standards. One widely used protocol is the IEC 61850 standard, which enables efficient communication between protection relays, substations, and control centers. This standard promotes interoperability, flexibility, and the integration of various intelligent devices within the grid. Other commonly used protocols include Modbus, DNP3, and IEC 60870-5, which facilitate data exchange and control functions between relays and other devices.

[1] proposes a MAS architecture for smart distribution networks and conducts a systematic review of its application in smart grid protection, while [2] utilizes a MAS to improve protection performance in dynamic operating conditions with weak source contribution. [3] presents a communication-based decentralized adaptive protection system design, with intelligent protection relays dynamically updating settings based on network configurations, while [4] introduces an intelligent distributed agent-based scheme using a multi-agent framework to enhance transient stability in smart grids with protection relays. The reviews and discussions in [5]–[8] examine the applications of adaptive protection techniques, including MAS, in power system protection while emphasizing the crucial role of coordination between protection devices in ensuring system integrity. In [9], a multi-agent system-based adaptive relay setting strategy considering distributed generation (DG) control status during faults to enhance protection system performance which is also substantiated through real-time simulation case studies is presented, while [10] introduces a bi-level multi-agent system-based protection scheme for maintaining coordination of overcurrent relays in the presence of DG resources. [11] discusses a novel three-stage setting method for overcurrent relays in wind farms, addressing coordination difficulties and maloperation causes, while [12] presents a peer-to-peer agent-based protection system for fault diagnosis and power restoration in distribution networks.

The multi-agent system proposed in [13] introduces a comprehensive power grid coordination and protection. It comprises several agents with specific roles and responsibilities that work together to ensure effective coordination among the relays by exchanging critical information and signals. This article focuses on implementing of an adaptive protection approach based on the concepts mentioned in [13]. In

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order to ascertain the feasibility and effectiveness of MAS techniques, a practical illustration is conducted using two STM32MPU boards. The demonstration involves setting up the two STM32MPU boards as two MAS-based protection relays to substantiate how MAS techniques can improve power grid protection.

The following sections of this article are structured as follows. The next section offers a detailed overview of the fundamental coordination processes among multiple agents during network configuration changes and fault occurrences. Subsequently, a practical demonstration section follows, showcasing the effective interaction among these agents in various scenarios.

II. ADAPTIVE MULTI AGENT SYSTEM BASED PROTECTION

The adaptive protection approach mentioned in [13] is organized into two cases: relay coordination during a change in network configuration and relay coordination during the occurrence of a fault. The subsequent sections provide detailed discussions of these cases.

A. Adaptive MAS-Based Protection Coordination for Network Configuration Changes

When changes occur in the network configuration, such as adding or removing loads and sources, it is essential to adjust the protection settings to ensure the grid's continued safe and reliable operation. Multiple agents work together to analyze the network configuration changes and calculate the necessary modifications regarding operating times and other protection parameters. Once the new settings are determined, they are transmitted to the higher-level relays using communication protocols such as IEC 61850 GOOSE (Generic Object-Oriented Substation Event). This protocol enables fast exchange of time-critical data among different relays and devices in the power system grid. Fig. 1 provides a concise flow chart illustrating the agents' interaction during a network configuration change.

During network configuration changes in a power system grid, the interaction among multiple agents is essential to ensure a coordinated and effective response. These interactions are facilitated through communication channels via the Communication Agent (CA), which interacts with other MAS-based relays, or the Device Agent (DA), which gathers network change information from switch or breaker status. The Network Configuration and Mapping Agent (NCMA) acquires the updated network status and communicates it to the Short Circuit Current Calculation Agent (SCCA) and Load Flow Calculation Agent (LFCA). The SCCA agent performs short circuit analysis, while the LFCA agent conducts load flow analysis. Based on the outputs from these agents, the Setting Calculation Agent (SCA) determines the updated protection settings for the relay.

Once the updated protection settings are determined, the SCA agent communicates this information to the Coordination and Optimization Agent (COA) and CA Agent. The COA agent receives the updated protection settings from the SCA agent and transmits this information to the Logic and Operating Agent (LOA). Based on the updated settings, the LOA agent implements the logic for operating the protection relays and circuit breakers. It ensures that the relays and circuit breakers respond appropriately to faults and network configuration changes, enabling effective fault detection and isolation. The CA Agent also sends this information over the network to other MAS-based relays, ensuring widespread awareness and coordination. This collaborative approach ensures a reliable and coordinated response to network configuration changes.

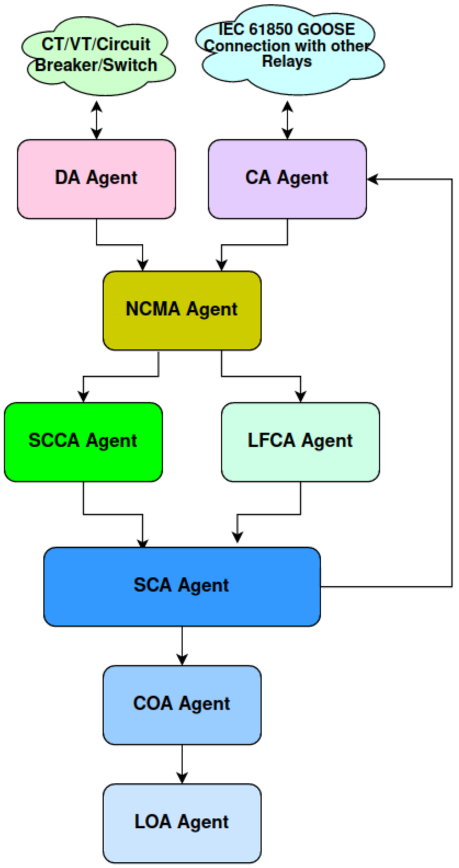


Fig. 1. Coordination among agents during network configuration change.

B. Adaptive MAS-Based Protection Coordination for Enhanced Fault Detection and Clearing

The coordination among MAS-based protection relays during a fault can be categorized into two cases. In the first case, lower-level and higher-level relays in the same direction of energy flow work together to clear faults. The second case involves the coordination among protection relays located in opposite directions of energy flows. Fig. 2 illustrates the various agents involved in detecting and clearing faults.

1) Coordination of Primary and Backup Relays: When a fault occurs in a power system grid, coordination among primary and backup relays is crucial to ensure quick and efficient fault clearing while preventing unnecessary tripping.

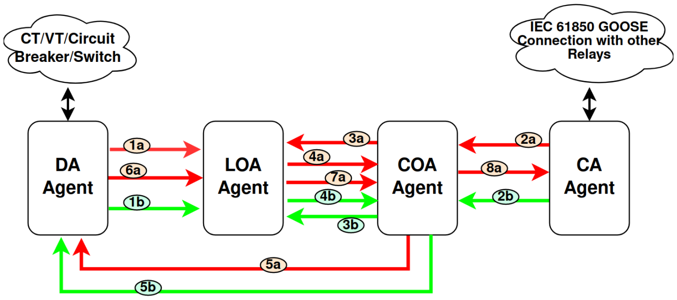


Fig. 2. Coordination among agents during fault detection.

In this case, lower-level protection relays are essential in detecting the fault and initiating the coordination process. As indicated by the red lines in Fig. 2, the coordination among multiple agents in this situation can be described as follows.

1a. The DA agent detects faults via CTs and VTs, which are then relayed to the LOA Agent.
2a. The COA Agent may receive blocking signals from the CA Agent. Blocking signals prevent unnecessary tripping actions by relays unaffected by the fault, ensuring coordinated responses.
3a. The LOA agent considers blocking signals from the COA agent and adjusts its logic accordingly.
4a. The LOA agent analyzes fault information and formulates trip logic for relay and circuit breaker operation. This logic is communicated to the COA agent for coordination and execution.
5a. The COA agent processes the trip logic and commands the DA agent to initiate necessary actions, such as tripping circuit breakers to isolate the faulted section.
6a. If tripping fails, the DA agent immediately informs the LOA agent of the situation.
7a. The LOA agent communicates the tripping failure to the COA agent, enabling reassessment and alternative measures.
8a. The COA agent instructs the CA agent to relay instructions to backup relays for appropriate actions, ensuring comprehensive fault management in the power system grid.

2) Coordination of Protection Relays in the Opposite Direction of Energy Flow: This coordination mechanism allows relays located in the opposite direction of energy flow to effectively detect and clear faults that would otherwise be challenging to identify solely based on their own protection settings. By leveraging the information from the opposite relay, these relays can enhance their fault detection capabilities. As indicated by the green lines in Fig. 2, the basic coordination among opposite relays is given as follows.

1b. When a fault occurs in the region between two opposite relays, the DA agents of each relay pass this information to the LOA agent, which performs further analysis and decision-making.
2b. The COA agent receives a “follow me” signal from the CA agent, which interacts with the opposite relay.
3b. The COA agent communicates the “follow me” signal to the LOA agent for coordination.
4b. The LOA agent analyzes the fault information and timing, formulating the appropriate trip logic, which it then sends to the COA agent.
5b. The COA agent commands the DA agent to initiate actions such as tripping circuit breakers.

III. IMPLEMENTATION OF MAS BASED PROTECTION

In order to illustrate the coordination among relays using MAS, an experimental demonstration setup is established with two STM32MP1 boards and a laptop connected via a local network. The setup is depicted in Fig. 3. The communication between the devices is facilitated through the IEC 61850 GOOSE protocol, enabling efficient data exchange and coordination. The boards are equipped with multi-core processors in which the cortex A7 cores run an embedded Linux operating system.

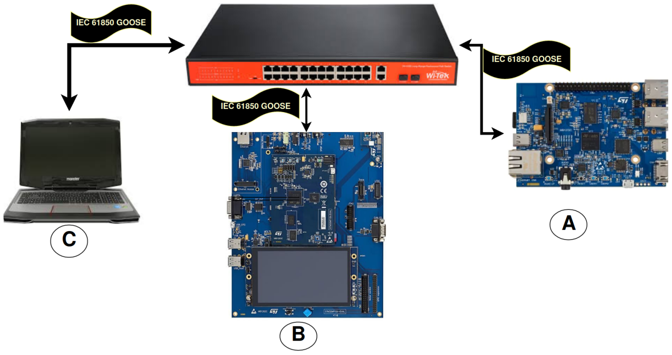


Fig. 3. Demonstration setup

To verify the abovementioned cases, STM32MP1 Board A is programmed as the primary relay, while STM32MP1 Board B is programmed as the backup relay. This configuration allows for the exploration of both Case A and Case B-1. The basic GOOSE message content, designed for illustrative purposes, comprises four parameters, as outlined in Table. I. It includes essential information such as NetConfig status, the relay's calculated operating time, Coordination Time Interval (CTI), and blocking signals. The NetConfig parameter represents the unsigned integer equivalent obtained by concatenating the values of CBs (CB1-CB2-CB3) in a binary form, as indicated in Table. II. For example, if CB1 is closed (1), CB2 is open (0), and CB3 is closed (1), the NetConfig value will be 101, which is equal to the decimal value 5. Along with the calculated operating time, CTI value, and blocking signal in the GOOSE message, the relays can share critical information necessary for coordination.

A. Case A

The setup involves Board A as the primary relay when the network configuration changes. In order to simulate the detection of switch or breaker status changes in the network,

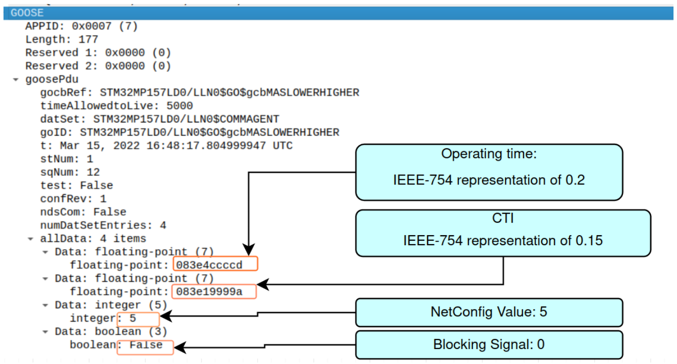
TABLE I
GOOSE MESSAGE STRUCTURE BETWEEN LOWER AND HIGHER LEVEL RELAYS

GOOSE MESSAGE 1 **(Relays along the same direction of energy flow)**
* NetConfig
* Operating Time
* Coordination Time Interval (CTI)
* Blocking Signal

TABLE II
CIRCUIT BREAKER STATUS INDICATOR FOR NETWORK CONFIGURATION

Time **Circuit Breakers**	$(t-2)^{th}$	$(t-1)^{th}$	t^{th}
CB1	0	1	1
CB2	1	0	1
CB3	0	1	1
NetConfig	2	5	7

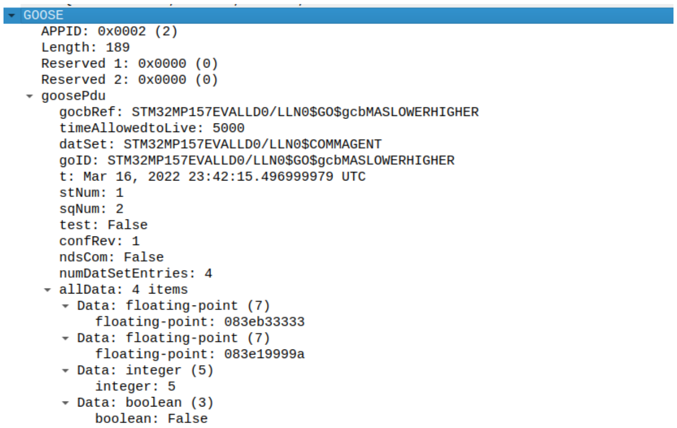
three digital input pins on Board A are configured accordingly, representing CB1, CB2, and CB3. For the demonstration, let's assume the calculated operating time and CTI values to be 0.2 seconds and 0.15 seconds, respectively. Assuming CB1 is closed (1), CB2 is open (0), and CB3 is closed (1), this configuration corresponds to a NetConfig value of 5. Since no fault condition is assumed for Case A, the blocking signal value will be 0. The GOOSE message published by the primary relay can be viewed in the captured network traffic data via Wireshark, as illustrated in Fig. 4, to visualize the transmission of relevant data. This GOOSE message includes information such as the NetConfig value (5), the calculated operating time (0.2 seconds), CTI (0.15 seconds), and the absence of a blocking signal (0).



```
GOOSE
   APPID: 0x0007 (7)
   Length: 177
   Reserved 1: 0x0000 (0)
   Reserved 2: 0x0000 (0)
 ▾ goosePdu
     gocbRef: STM32MP157LD0/LLN0$GO$gcbMASLOWERHIGHER
     timeAllowedtoLive: 5000
     datSet: STM32MP157LD0/LLN0$COMMAGENT
     goID: STM32MP157LD0/LLN0$GO$gcbMASLOWERHIGHER
     t: Mar 15, 2022 16:48:17.804999947 UTC
     stNum: 1
     sqNum: 12
     test: False
     confRev: 1
     ndsCom: False
     numDatSetEntries: 4
   ▾ allData: 4 items
     ▾ Data: floating-point (7)
         floating-point: 083e4ccccd
     ▾ Data: floating-point (7)
         floating-point: 083e19999a
     ▾ Data: integer (5)
         integer: 5
     ▾ Data: boolean (3)
         boolean: False
```

Fig. 4. Network traffic data for GOOSE message published by primary relay

Upon receiving the network configuration change information from Board A, which functions as the primary relay, Board B, acting as the backup relay, performs calculations to determine the new operating time. In this case, let's assume the calculated operating time for Board B to be 0.35 seconds. Board B adjusts its protection settings based on this updated operating time. To ensure coordination among the relays, Board B also relays this updated information to the higher-level relays in the network. This information exchange allows the higher-level relays to stay informed about the changes and adjust their protection settings accordingly. Fig. 5 represents the captured network traffic data, which depicts the transmission of the updated operating time and protection settings from Board B to the higher-level relays.



```
▾ GOOSE
    APPID: 0x0002 (2)
    Length: 189
    Reserved 1: 0x0000 (0)
    Reserved 2: 0x0000 (0)
  ▾ goosePdu
      gocbRef: STM32MP157EVALLD0/LLN0$GO$gcbMASLOWERHIGHER
      timeAllowedtoLive: 5000
      datSet: STM32MP157EVALLD0/LLN0$COMMAGENT
      goID: STM32MP157EVALLD0/LLN0$GO$gcbMASLOWERHIGHER
      t: Mar 16, 2022 23:42:15.496999979 UTC
      stNum: 1
      sqNum: 2
      test: False
      confRev: 1
      ndsCom: False
      numDatSetEntries: 4
    ▾ allData: 4 items
      ▾ Data: floating-point (7)
          floating-point: 083eb33333
      ▾ Data: floating-point (7)
          floating-point: 083e19999a
      ▾ Data: integer (5)
          integer: 5
      ▾ Data: boolean (3)
          boolean: False
```

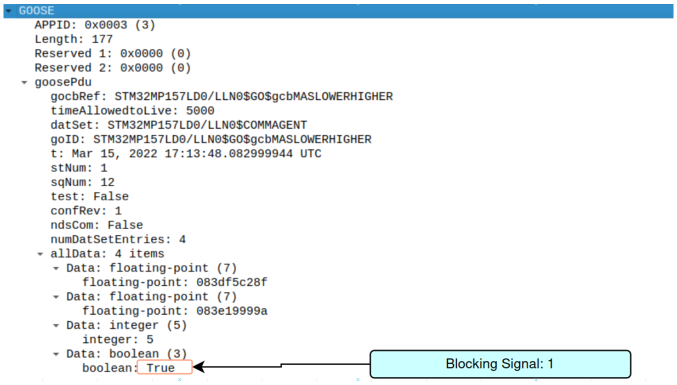
Fig. 5. Network traffic data for GOOSE message published by backup relay

In order to optimize efficiency, the relay can store the protection setting values previously calculated for a specific NetConfig value. By doing so, if the same NetConfig value reemerges in the future, the relay can retrieve the precalculated protection settings instead of performing the calculations again. This approach eliminates the need for redundant calculations, reducing processing time and improving overall efficiency in handling repeated NetConfig scenarios. The communication and synchronization among the relays enable them to adapt to network configuration changes and maintain a coordinated power system operation.

B. Case B-1

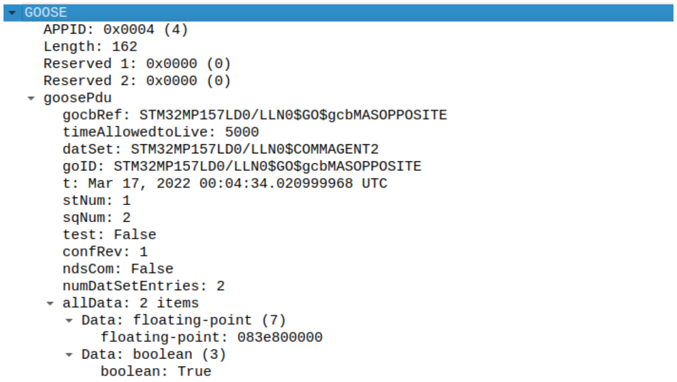
Let's consider a scenario where a fault happens in the primary protection region of the primary relay, represented by Board A. For this particular case, let's assume the calculated operating time to be 0.12 seconds. Since the fault occurs within the primary protection section and the network configuration remains unchanged, the NetConfig value will remain 5, as assumed earlier. Additionally, the CTI is assumed to be 0.15 seconds. With the fault's occurrence, the GOOSE message's blocking signal will be set to 1. This signal indicates that the primary relay has detected the fault and initiated a blocking action to prevent tripping of the backup relay. The captured network traffic data in Fig. 6 depicts the GOOSE message containing the information such as the NetConfig value (5), calculated operating time (0.12 seconds), CTI (0.15 seconds), and the presence of a blocking signal (1).

By examining the GOOSE message in the captured network traffic data, the coordination and communication between the primary and backup relays during a fault can be observed. This information exchange allows the relays to coordinate their actions, ensuring that the backup relay does not trip and



```
GOOSE
    APPID: 0x0003 (3)
    Length: 177
    Reserved 1: 0x0000 (0)
    Reserved 2: 0x0000 (0)
  goosePdu
      gocbRef: STM32MP157LD0/LLN0$GO$gcbMASLOWERHIGHER
      timeAllowedtoLive: 5000
      datSet: STM32MP157LD0/LLN0$COMMAGENT
      goID: STM32MP157LD0/LLN0$GO$gcbMASLOWERHIGHER
      t: Mar 15, 2022 17:13:48.082999944 UTC
      stNum: 1
      sqNum: 12
      test: False
      confRev: 1
      ndsCom: False
      numDatSetEntries: 4
    allData: 4 items
      Data: floating-point (7)
          floating-point: 083df5c28f
      Data: floating-point (7)
          floating-point: 083e19999a
      Data: integer (5)
          integer: 5
      Data: boolean (3)
          boolean: True
```

Fig. 6. Network traffic data for GOOSE message published by primary relay during fault



```
GOOSE
    APPID: 0x0004 (4)
    Length: 162
    Reserved 1: 0x0000 (0)
    Reserved 2: 0x0000 (0)
  goosePdu
      gocbRef: STM32MP157LD0/LLN0$GO$gcbMASOPPOSITE
      timeAllowedtoLive: 5000
      datSet: STM32MP157LD0/LLN0$COMMAGENT2
      goID: STM32MP157LD0/LLN0$GO$gcbMASOPPOSITE
      t: Mar 17, 2022 00:04:34.020999968 UTC
      stNum: 1
      sqNum: 2
      test: False
      confRev: 1
      ndsCom: False
      numDatSetEntries: 2
    allData: 2 items
      Data: floating-point (7)
          floating-point: 083e800000
      Data: boolean (3)
          boolean: True
```

Fig. 7. Network traffic data for GOOSE message published among opposite relays during fault.

maintains its standby status while the primary relay handles the fault.

C. Case B-2

To demonstrate a fault scenario in the region between relays located in the opposite direction of energy flow, Board A and B are configured to function as two relays in this opposite direction. The GOOSE message, explicitly designed for demonstration purposes, includes two key parameters: the "follow me" signal and the relay's calculated operating time. Table. III outlines these parameters, which are crucial in coordinating the relays during fault occurrences.

TABLE III
GOOSE MESSAGE STRUCTURE BETWEEN OPPOSITE RELAYS

GOOSE MESSAGE 2 (Relays in the opposite direction of energy flow)
* Operating Time
* Follow-me Signal

In the event of a fault in the region between these two relays, each relay might initially assume that the fault has occurred within its primary protection region. However, coordination among these relays is essential to avoid confusion and ensure accurate fault identification. If the first relay, specifically Board A, detects a fault condition ahead of the other relay (Board B), it initiates the transmission of a GOOSE message. For illustration, the content of this GOOSE message includes two specific attributes: a calculated operating time of 0.25 seconds and a follow-me signal set to a high state. This coordination ensures that both relays clearly comprehend the fault location and can take appropriate actions accordingly. Fig. 7 represents the captured GOOSE message via Wireshark, depicting the exchanged information between the relays during their coordination.

By examining the GOOSE message in Fig. 7, the coordination process between the relays located in the opposite direction of energy flow can be observed. This coordination helps mitigate confusion and enables accurate fault identification and clearance.

IV. CONCLUSION

Modern protection relays have evolved to offer multi-functional capabilities, cutting-edge communication features, and diverse fault detection techniques, ensuring the safety and reliability of electrical networks. These relays enable interoperability and seamless communication within the grid, resulting in improved grid management and optimized power system operations. The use of adaptive multi-agent systems (MAS) in intelligent grid management can improve control, supervision, and decision-making processes. The practical implementation of a MAS-based protection approach demonstrates its viability and efficacy in analyzing real-time data, formulating decisions, and coordinating agents. Integration with communication protocols like IEC 61850 GOOSE further enhances real-time information exchange for rapid fault detection, isolation, and restoration. The adoption of MAS and advanced communication protocols highlights the potential of intelligent and adaptive systems in revolutionizing power grid protection.

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