A Multiagent and IEC 61850-based fault location and isolation system for distribution network with high PV integration

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A Multiagent and IEC 61850-Based Fault Location and Isolation System for Distribution Network with High PV Integration – A CHIL Implementation

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Abstract—The ever-increasing integration of renewable distributed generation sources, for instance photovoltaic systems, into the French medium-voltage distribution has imposed several challenges to its conventional fault location and isolation system. Several researches have indicated that the present fault location and isolation system would be unable to deal with the bidirectional characteristics of the fault currents in such multi-source distribution network. On the other hand, there has been a considerable number of recently published papers that proposed to apply multiagent system and IEC 61850 communication standard for tackling these issues and the further practical applications are rather promising. However, the validation of these approaches was mainly carried out in software environments. Although, a few papers have proved the effectiveness of their systems by using Hardware-In-the-Loop technology, the interaction amongst realistic hardware equipment such as IEDs and agents was often ignored. Therefore, this paper aims at developing a novel MAS- and IEC 61850-based fault location and isolation system that can effectively operate in distribution network with high penetration of photovoltaic systems.

Keywords— IEC 61850, GOOSE message, fault location and isolation system, multiagent system, photovoltaic system;

I. INTRODUCTION

Since faults in distribution network account for over 80 percent of the total power outages in power systems [1], the System Average Interruption Duration Index (SAIDI) of the whole electrical power system largely relies upon the performance of the fault location and isolation system (FLIS) of the distribution networks. At the moment, the most popular kind of FLIS in French distribution network is mainly based on the coordination between the recloser located at the head of the feed-in feeder and the remotely controlled switches (RCS) installed along the feeder [2]. Thanks to the development in power electronics and renewable energy technologies, the integration of distributed energy resources (DER) into the distribution network has become a dominant trend and thus increased the complexity of the distribution networks. The traditional single-source radial distribution network has been transformed into multi-source active one. The fault currents will be contributed by several power sources. This properly leads to the mal-operation of the existing FLIS faults due to the lack of directional facility. Consequently, a major upgrade on the current generation of the FLIS should be taken into consideration.

Generally, FLIS can be divided into three categories including centralize, decentralized and distributed. The current French FLIS falls into the centralized group. With a high level of complexity and sensitivity of new active distribution networks, a large amount of measurements and binary inputs, e.g. the status position of the RCS, fault information detected by the fault indicators or power injected by the photovoltaic (PV) systems, should be transferred to the control center for fault location and isolation purposes. Nonetheless, sending such a huge volume of data requires a dedicated high bandwidth communication channel. Moreover, high computation capacity of hardware devices is needed for processing this large amount of data to issue controlling commands. An additional disadvantage of the centralized FLIS is that it may face with the so-called single-point of failure. Therefore, decentralized and distributed FLISs, which processing data and decision-making locally, would be a more effective approach.

Recently, several researches that applied multi-agent system (MAS) for developing new distributed FLISs have been published. The IEC 61850 Generic Objective Oriented Substation Event (GOOSE) protocol was also utilized for implementing communication channel between these agents. Ref [3] and [4] present multi-agent based FLISs, in which the agents take action once have received the lock-out signal from the feeder recloser. A multiagent automation architecture based on IEC 61850/61499 intelligent logical nodes (LNs) is presented in [5]. The authors proposed to implement additional intelligent logical nodes that are responsible for making decision and negotiating with other agents. The authors also elaborated on the coordination between the agents as a complete system. A paper in [6] describes an agent-based-distributed FLIS using IEC 61850 GOOSE protocol. Several agents are installed along the feeders and communicate among each other by using GOOSE protocol. The authors also proposed to add a directional element to the sectionalizing agent that can assist the agent in differentiating the fault direction in case of feeders with high integration of DERs. Ref [7] presents a new approach that based on the comparison of direction information shared between the adjacent agents via IEC 61850 GOOSE protocol.

It is evident that although the aforementioned approaches have offered innovative approaches, the evaluation process was mainly conducted in software environment such as Matlab/Simulink, Real Time Digital Simulator (RTDS) or Java Agent Development Framework (JADE). The performance of the communication network, which occupies a crucial role in exchanging information amongst the agents as well as the agents and central controller, was not taken into consideration. The interaction between the real agents (real controller devices) and digital relays or Intelligent Electronic Devices (IEDs) within a FLIS, which can result in unwanted behaviors, was also ignored.

Currently, the Controller-Hardware-In-the-Loop (CHIL) is a rather effective approach for investigating and validating the performance of a system that consists of several realistic hardware devices and simulation tools. Some CHIL-based investigations into adaptive protection were conducted in [8]-[9]. However, the application of CHIL for evaluating new

generations of FLIS, which are based on MAS and IEC 61850 communication, has been infrequently mentioned.

Therefore, in this paper the authors propose a MAS-based FLIS that applies IEC 61850 GOOSE message based communication infrastructure. This FLIS is determined to deal with the bidirectional characteristic of the fault current in the today's dominant active distribution network. The outage duration can be shortened thanks to the automatic operation of the proposed system, consequently improving the SAIDI of the network. In order to confirm the functional performance and the interoperability of the multi hardware-based, functional performance testing is mandatory. Hence, the proposed FLIS is implemented in a laboratory platform with CHIL setup. The CHIL platform incorporates hardware-based model of MAS, digital relays and realistic IEC 61850 GOOSE message-based communication network. The testing results shows that the proposed FLIS properly has detected and isolated all the faults under a variety of fault scenarios. The paper is structured as follows. Section II describes the formulation of the proposed FLIS. Section III presents structure of the agents and the IED needed for the developed system. The operation of the designed system is detailed in section IV. Section V concludes the paper while also suggesting some points that further should be taken into consideration.

II. THE PROPOSED MAS AND IEC 68150-BASED FLIS

In the French distribution network, the allocation of RCS on each feeder is determined by calculating the product of the power injected into the feeder and its length. This product is called equivalent grid bag which is located between two closest sectionalizers [2]. The sectionalizers are remotely controlled by the binary inputs received from the control center. These signal are generated manually by the system operator after analyzing the fault indications received from the fault indicators at the sectionalizer locations. As mentioned in [2], the operation of the French traditional fault location, isolation and restoration system in case of permanent faults can be normally divided into three phases including remote controlled action, manual action, and remedial actions. The first phase, which is automatic fault location and isolation, often lasts for about from three to five minutes.
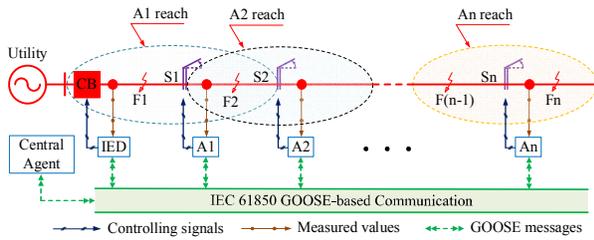

Figure 1. The structural diagram of the proposed FLIS

IEC 61850 communication standard is now being widely used in many utility companies. In particular, GOOSE messaging has been applied not only for control and monitoring of primary equipment and IED status but also for status interaction between IEDs including protective relays by replacing the conventional method of using binary inputs/outputs and wires with communication by GOOSE messages over Ethernet cables/fibres. Thus, in the proposed algorithm, the operational coordination of the agents and IED will be mainly based on exchange of their status using

GOOSE messages. The authors propose to replace all the fault indicators and the controller of the RCSs by the IEC 61850-based agents that will be described in section III. This means that all sectionalizers are locally governed by the agents. A central agent called control center also needs to be constructed at the substation in order to coordinate the operation of the IED and the agents. The structural diagram of the proposed FLIS is show in Fig. 1.

Fig. 1 indicates that each agent protection reach covers two sections that physically and directly relate to its sectionalizer. A fault is considered as internal if it occurs inside the agent reach, otherwise fault is regarded as external. The agent operation is based on the information exchanged with the feeder IED and the adjacent agents. The agents continuously monitor the feeder operating condition by comparing the RMS values of the measured currents with the predefined operating threshold. Meanwhile, it also subscribes to the GOOSE messages published by the feeder IED and the two neighboring agents. The detailed operation mechanism of the proposed FLIS will be elaborated in section IV.

III. STRUCTURE OF THE IEC 61850-BASED IED AND AGENTS REQUIRED FOR THE PROPOSED FLIS

The IED and the agents are modeled by using the LNs as specified in IEC 61850-5 standard. Moreover, apart from detecting fault inception as conventional fault indicator, each agent should be capable of determining fault direction and communicating with external equipment, i.e. the IED and the adjacent agents. An IEC 68150-based architecture of a feeder IED and an agent is illustrated in Fig. 2, whose LNs are detailed in Table 1.
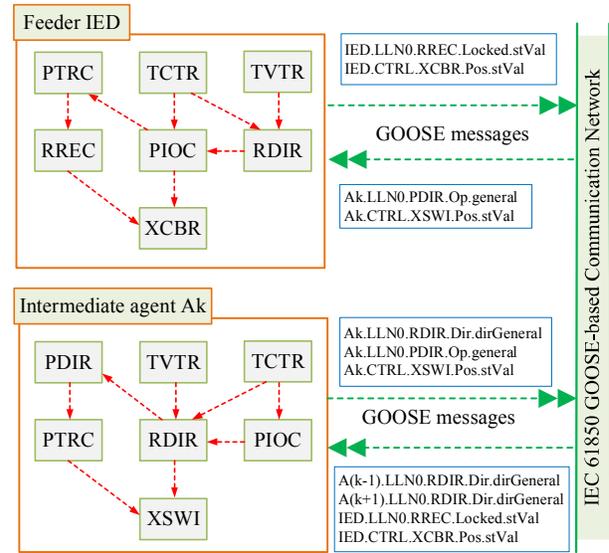

Figure 2. IEC 61850-based IED and agent models

There are two kinds of agents including marginal and intermediate. The former type refers to two agents, one right after the IED (A1) and one at the final line-section (An). The intermediate agents (Ak) are those located between the two marginal agents. The marginal agents only subscribe the GOOSE messages reported by one agent that is closest to them. Also, the working principle of their direction comparison block differs from that of the intermediate agents. When the first agent (A1 in Fig. 1) determines a reverse fault, it will state immediately that the fault is between the IED and

its position without comparing the fault direction with that received from A2. On the other hand, when the last agent (An in Fig. 1) senses a fault in forward direction, it can conclude that the fault has occurred in the last section but not needs to consult about the fault direction from the agent A(n-1).

TABLE I.   IED AND AGENT LOGICAL NODE DESCRIPTION

LN	Function	LN	Function
TCTR	Sample currents	TVTR	Sample voltages
PTOC	Overcurrent function	RREC	Autoreclosing function
RDIR	Directional element	PDIR	Direction comparison
XCBR	Circuit Breaker	XSWI	Sectionalizer
PTRC	Protection trip conditioning		

The LNs TCTR and TVTR are capable of filtering, sampling and sending the currents and voltages, which are provided by the measurement transformers to the LNs PTOC and RDIR. The LN XCBR represents specific data of the CB including its position and controlling signal status. The LN RREC is auto-reclosing function. The LN PDIR assumes responsibility for direction comparison and faulty area detection. Finally, the PTRC combines the "operate" outputs of one or more protection blocks to a final tripping signal to be delivered to the LN XCBR.

IV. THE OPERATION OF THE PROPOSED FLIS

As mentioned earlier, the conventional FLIS cannot deal with the fault in the multi-source distribution feeders.

TABLE II.   IED AND AGENT GOOSE MESSAGES

Message	Description
	Values
IED	
IED.CTRL.XCBR.Pos.stVal	CB position
	0=intermediate | 1=open | 2=closed | 3=faulty
IED.LLN0.RREC.Locked.stVal	Signal indicates that autoreclosing functions is locked out
	1=true | 0=false
Agent	
Ak.LLN0.RDIR.Dir.dirGeneral	Direction values
	1=forward | 0=backward
Ak.LLN0.PDIR.Op.general	Operate (decision from all agents that the surrounded line-section is faulted)
	1=true | 0=false
Ak.CTRL.XSWI.Pos.stVal	Switch position
	0=intermediate | 1=open | 2=closed | 3=faulty
Ak.CTRL.RSWF.OpEx.general	Switch failure protection
	1=true | 0=false

For instance, for a permanent fault at F1 as shown in Fig.1, all the fault indicators will detect the fault. Without the fault direction information, the system operator fails to determine in which grid bag the fault is located and thus cannot take a

final decision on which sectionalizers to be opened to clear the fault. If it could be assumed that the system operator has successfully handled the fault, the fault clearance time can be up to several minutes, negatively affecting the system SAIDI.

Therefore, the information exchange amongst the IED and agents as well as the ability of automated operation of agents without the intervention of system operator in the first stage of system automation procedure are of significant importance for struggling against the bidirectional characteristic of fault currents and improving the power supply quality. Therefore, the authors proposed to implement a GOOSE message-based communication channel between the IED and agents. The details of the GOOSE messages are described in Table II according to the IEC 61850-7-4 standard. A certain agent Ak should subscribe to the GOOSE messages transmitted by the IED and its neighboring agents, i.e. A(k-1) and A(k+1). On the other hand, the IED must subscribe all the status of the sectionalizers reported by the agents. The operational logic diagrams of an agent and the control center are illustrated in Fig. 3 and Fig. 4 respectively.
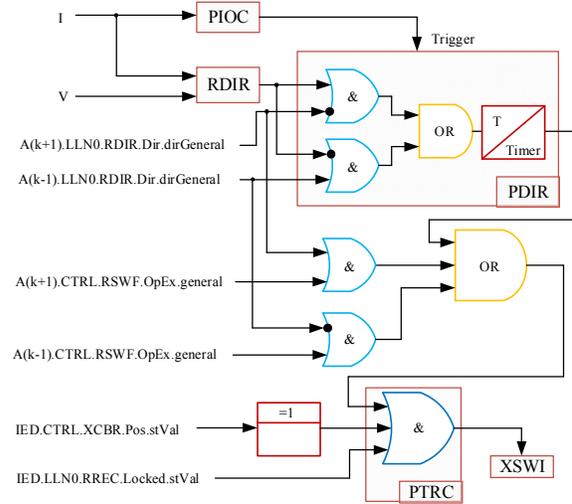

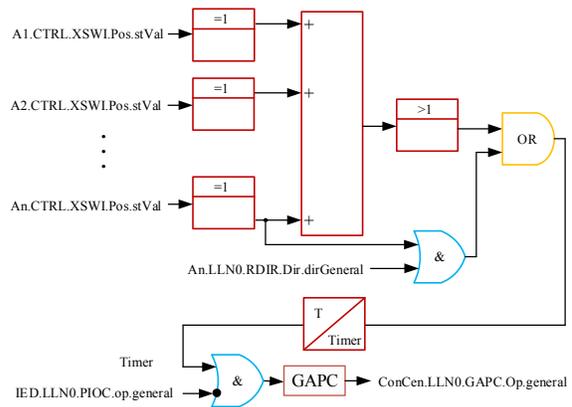Figure 3.   The functional logic diagram of an agent

Figure 4.   The functional logic diagram of the control center

In normal condition, the operating current is below the predefined setting threshold and thus the agent LN PIOC is not initiated. The attribute *general* of the data *PDIR.Op* is held at *general*=False and thus the opening signal transferred to the LN XSWI is locked. The operation of the whole system in

case of transient and permanent faults is explained in the following subsections.

A. Transient faults

When a temporary fault occurs, the IED's LN RREC will be initiated by its LN PTOC and go through autoreclosing attempts. In the meantime, the LN PIOC of each agent Ak also detects the fault and initiates the LN PDIR to compare the direction value transmitted by the LN RDIR and those included in the GOOSE messages it subscribes to (Fig. 3), i.e. *A(k-1).LD1.RDIR.Dir.dirGeneral* and *A(k+1).LD1.RDIR.-Dir.dirGeneral*. At this step, each agent's LN PDIR has already established whether the fault is external or internal. However, since a temporary fault will be extinguished after a definite number of autoreclosing trials, the value *IED.LLN0.RREC.Locked.stVal* is still unchanged, i.e. *stVal*=False. As a result, the *Boolean* value, which each agent's LN PTRC receives, is False. Thus all the sectionalizers remain closed.

On the other hand, thanks to the fault direction value included in the data *RDIR.Dir* (*dirGeneral*=1 or 0) published by all the agents, the control center can determine in which section the fault happened and carry out suitable remedial actions for preventing the fault from appearing again.

B. Permanent faults

In case of a persistent fault, the RREC goes into Lockout state after the final reclosing attempt and thus the GOOSE message *IED.LLN0.RREC.Locked.stVal* will change from value of 0 to 1 (true). At the same time, since the CB is opened after the last RREC trial, the value in the GOOSE message *IED.LLN0.XCBR.Pos.stVal* is equal to 1. As a consequence, those agents, which have detected an internal fault, will be allowed to command opening signals to their sectionalizer, isolating the fault.

The next step after the fault isolation is to reclose the CB. The control center is responsible for this task. Normally, the control center supervise the operation of the CB and all the sectionalizers by subscribing all the GOOSE message indicating the CB's and sectionalizers' positions. These messages are *Ak.CTRL.XSWI.Pos.stVal* and *IED.LLN0.-PIOC.op.general*. Once all the conditions have been fulfilled, the control center will generate a closing command to the CB in order to reconnect the unaffected zones to the grid. The total operation time from the inception of fault to the instant when the contacts of the sectionalizers fully open will be evaluated in the section following section.

C. Sectionalizer failure prevention

The sectionalizer may fail to trip due to various causes, for instance, operating component failure, defective DC source. Faulty line-section must be isolated under sectionalizer failure condition. In this case, an appropriate adjacent sectionalizer should be tripped, which can be realized by implementing a new dedicated sectionalizer failure protection (RSWF) in each agent. This kind of protection is similar to the CB failure protection (RBRF) according to IEC 61850-7-4. The RSWF logic is presented in Fig. 5. The working principle of the RSWF function of the agent A3 can be explained by considering a permanent fault at F3 (Fig. 1).

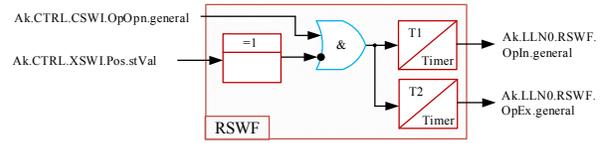Figure 5.   The agent RSWF logic

The RSWF is initiated by the opening signal from the *CSWI.OpOpn* (general=true). At the first step, the sectionalizer failure protection will send a reopening order to the sectionalizer (*A3.LLN0.RSWF.OpIn.general*) after a certain time delay. If it did not open after the second time delay is elapsed, the message *A3.LD1.XSWI.Pos.stVal* still has a value different from 1 (Table II). The attribute *"general"* of the data *A3.LD1.RSWF.OpEx* will change to 1 (true). Fig. 3 shows that the agent A2, which is set to subscribe to this message, will incorporate it with the true value of the message *A2.LD1.RDIR.Dir.dirGeneral* and operate to open the sectionalizer S2. The fault F3 is isolated and then the control center can reclose the CB because both data attributes A2.*LD1.XSWI.Pos.stVal* and *A4.LD1.XSWI.-Pos.stVal* are true (1) and the output of the addition bock, therefore, will be certainly larger than 1.

V.   CHIL Real Time Testing Platform

In order to evaluate and prove the effective and reliable performance the proposed system, a CHIL real time simulation platform has been implemented utilizing Opal-RT's eMEGAsim simulator OP 5000, an ABB REF615 relay and three ARM-based computers as shown in Fig. 6.
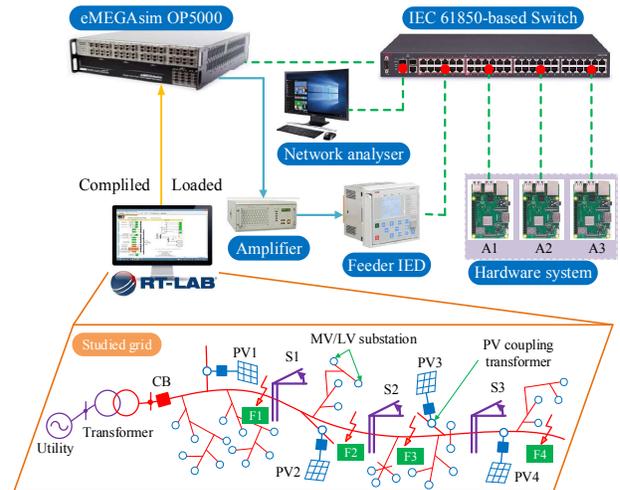

Figure 6.   CHIL real time testing platform

A. The studied feeder

The analyzed feeder represents a typical French MV rural distribution overhead line fed by a 63 kV source through a 63/20 kV transformer. It is modeled by several PI model-based line sections. The total load active and reactive power are 4401 kW and 829 kVar respectively. The loads are distributed along the feeder. The feeder is sectionalized into 4 zones which are protected by 3 agents. Four PV systems of 440 kW rating each are integrated into these 4 zones. All the PV systems are modeled as voltage-controlled current sources with the fault currents limited to two times their rated currents. In addition, the simulated PV systems should be disconnected in 0.2 s after the fault inception. This is for the

transient faults to disappear once the CB has opened by isolating them from fault current feeding sources like PV systems in our case.

On the other hand, the CB and the sectionalizers with their controlling circuits are simulated in the OPAL simulator. However, we set the operation time of the CB and the sectionalizers to 0.03s and 0.1s respectively in order to take into account their practical operation times.

B. The feeder IED and agents

All the LNs and the IEC 61850-based communication socket of each agent are modeled using Python programming language and embedded in ARM-based computers. The IEC 61850-based communication socket enables these agents to generate, publish and subscribe to GOOSE messages. The agents will receive current and voltage measurements from OPAL via an Ethernet switch. These measurement values are filtered by an integrated full window length cosine filter in order to remove aliased signals. The sampling rate is set at 1000 Hz so the window length equals 20.

Considering the overcurrent-based protection function of the IED, the time delay is chosen as 0.5s as currently being used in practice in French distribution networks. The IED's RREC function that follows the PTOC trip has two cycles, one fast with 0.3s wait and one slow with 10s delay.

In this paper, the authors only focus on validating the overall performance of the proposed FLIS, therefore an Ethernet-based LAN is applied for communication between the agents and the feeder IED. However, in order to account for the GOOSE propagation time between the agents and the IEDs (outside the substation area), the GOOSE wait time has been set to 100 ms.

VI. RESULTS AND DISCUSSIONS

A. The performance of IEC 61850 GOOSE-based communication amongst IED and agents

In order for the feeder IED and the ARM-based agents being able to publish the GOOSE messages over the network, we need to group the messages of each into data sets and configure GOOSE control block (GCB). Each ARM-based agent and also the feeder IED have MAC IP address to be included into the GCB. The performance of the GOOSE-based communication capability of the IED and the ARM-based agents was tested using Wireshark software tool. A segment of the data set of the GOOSE messages published by the feeder IED is illustrated in Fig. 7.


```
∨ Ethernet II, Src: AbbOy/Me_25:08:a2 (00:21:c1:25:08:a2), Dst: Iec-Tc57_01:00:00 (01:0c:cd:01:00:00)
  > Destination: Iec-Tc57_01:00:00 (01:0c:cd:01:00:00)
  > Source: AbbOy/Me_25:08:a2 (00:21:c1:25:08:a2)
    Type: IEC 61850/GOOSE (0x88b8)
∨ GOOSE
    APPID: 0x0001 (1)
    Length: 149
    Reserved 1: 0x0000 (0)
    Reserved 2: 0x0000 (0)
  ∨ goosePdu
      gocbRef: AA1J1Q01A1LD0/LLN0$GO$GCB_Dataset
      timeAllowedtoLive: 11000
      datSet: AA1J1Q01A1LD0/LLN0$Dataset
      goID: AA1J1Q01A1LD0/LLN0.GCB_Dataset
      t: Feb 25, 2019 17:34:32.688160002 UTC
      stNum: 1
      sqNum: 8505
      test: False
      confRev: 300
      ndsCom: False
      numDatSetEntries: 2
    ∨ allData: 2 items
      ∨ Data: bit-string (4)
          Padding: 6
          bit-string: 00
      ∨ Data: boolean (3)
          boolean: False
```

Figure 7.   Sniffer GOOSE messages in Wireshark

The tests have shown that the IED feeder and the agents successfully published and subscribed to the required GOOSE that were previously presented in the section IV.

B. Performance of the proposed system

The proposed FLIS has proved its effectiveness because it has successfully dealt with various fault scenarios. Some of testing results conducted for different fault conditions are tabulated in Table III and graphically shown in Fig. 8 and 9.

TABLE III.   TESTING RESULTS

Fault location	Operation sequences	Operation time, s
F1	CB opens → RREC operated & locked out → CB opens	12.03
F2	CB opens → RREC operated & locked out → CB opens → S1 & S2 opened → CB closed	13.68
F3	CB opens → RREC operated & locked out → CB opens → S2 & S3 opened → CB closed	13.52
F4	CB opens → RREC operated & locked out → CB opens → S3 opened → CB closed	13.64

The total operation time is computed starting from the instant at which the fault happens to the time when the CB fully reclosed after the successfully operation of concerned sectionalizers. It is evident that the fault clearance time of the proposed system has been reduced compared with 3 minutes or more of the present one.
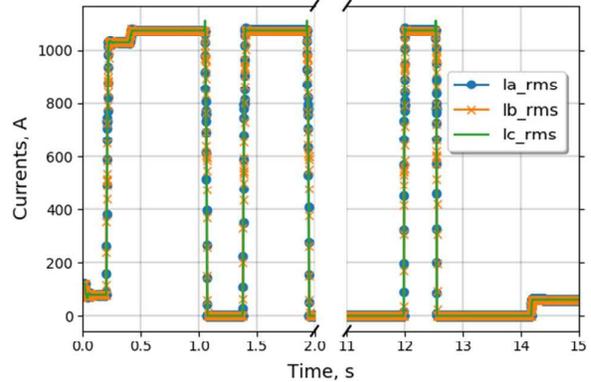

Figure 8.   IED time-current curves in case of three-phase fault

Fig.8 presents the current-time curves measured by the feeder IED for a permanent three-phase fault at F3 (Fig. 6) with fault resistance of 10 Ω. It clearly shows that after the fast and then slow cycle, the autoreclosing function of the IED is locked out and the IED tripped the CB again. Once the CB had already opened, the agents A2 and A3 operated to open the sectionalizers S2 and S3 respectively. At the final step, the control center reclosed the CB; however, the power supply was recovered to only a part of total customers who were located between the IED and the sectionalizer S2. This is demonstrated by the decrease of the currents after 6.88s.

The results for a permanent single-phase-to-ground fault are also presented in Fig. 9.
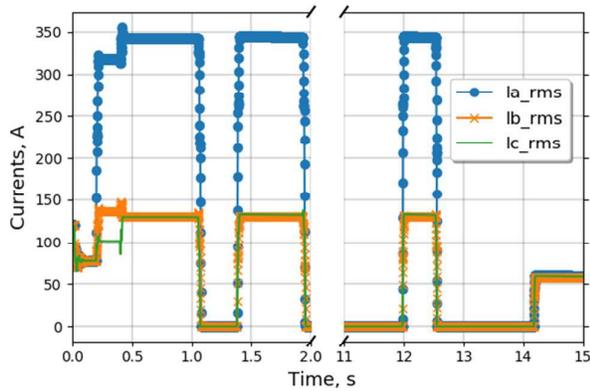
Figure 9.   IED time-current curves in case of phase-to-ground fault

Similarly, the agents correctly detected the faulty line-section and then operated the sectionalizers to open, isolating the fault.

VII. CONCLUSION AND SUGGESTIONS

In this paper, a new MAS and IEC 61850 GOOSE message-based FLIS is proposed. The presented scheme developed new operation mechanism for the IED and the agents that is mainly based on the local measurements and the fault direction information exchanged via the GOOSE message-based communication. The results yielded from the CHIL real time testing show that the proposed FLIS system can properly deal with the faults under various fault scenarios. The fault location and isolation time is reduced.

However, the impacts of communication network in terms of communication losses, and delay and other severe fault conditions have not been taken into account. Hence, further studies should focus on these above issues. In addition, an accurate fault point location algorithm also needs to be developed based on the proposed scheme.

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