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Adaptive Multi-Agent-Zonal Protection Scheme for AC Microgrids

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Keywords

«Adaptive protection», «Decentralized protection», «Microgrid», «Multi-Agent System», «Real-time simulation»

Abstract

This study aims to develop an adaptive protection scheme that guarantees the correct operation of electrical protections for a microgrid (MG), according to its topological changes. For this purpose, the concept of multi-agent decentralized adaptive protection is used through the Gaia methodology, which offers autonomy in the decision-making process. The IEEE 13 Node Test Feeder network is used to evaluate the electrical protections operation, and six directional overcurrent relays (50/51/67) were integrated to protect the necessary system areas. It is shown that the inclusion of distributed energy resources (DER) in the network modifies the nominal currents in each relays proposed and cause loss of selectivity and coordination of the scheme. The proposed algorithm is adequate, and its behaviour could be evidenced through tests carried out offline using the ETAP RT software and in real-time simulation using the Hypersim software.

Introduction

One of the current challenges in microgrid (MG) installation is the development of reliable protection and control schemes that guarantee the correct operation of these micropower systems [1]. The protection schemes used in traditional systems, i.e., with radial power flows, are designed to work with high levels of fault currents [2] and operate in such a way that when a fault occurs, they can isolate the affected areas to maintain continuous service in the rest of the network and reduce the probability of equipment damage. However, power system operation is dynamically altered by the incorporation of an MG, and traditional protection schemes suffer operational failures [3].

Modern protection schemes have been developed for systems that integrate MGs, and adaptive protection schemes (APS) are one of these modern technologies. These schemes can integrate digital relays, sensors, and communication protocols to monitor and control the status of the protections [4]. The advantages of adaptive schemes over traditional ones are currently known [5], [6]. Adaptive schemes can adopt intelligent algorithms, quickly adjust to network changes, and modify protection settings. However, many of these schemes require communication protocols that generate uncertainty in information and data latency [7]. Currently, there is a rising trend towards real-time simulation (RTSim) to evaluate the adaptive protection response and their communication systems in these networks before their implementation [8], [9]. However, few decentralized adaptive multi-agent electrical protection schemes use RTSim equipment to validate the operation before implementation in MGs.

The objective of this study is to develop a Multi-Agent-Zonal adaptive protection scheme that can be validated through an RTSim environment, to ensure service reliability and decrease operational costs. For real-time simulation, we used the IEEE 13-node test feeder and integrated DER using the concept of software in the loop (SIL). In addition, we integrated six Intelligent Electronics Devices (IEDs) with the directional overcurrent function (50/51/67) and simulated three-phase faults in different network points.

In this document, we also illustrate the interaction between the communication protocol IEC 60870-5-104, the JADE agent software, and the Hypersim software, in the analysis of the behavior of communication protocols in real time with algorithms written in Java programming language. To our knowledge, this has not been previously performed for electrical protection. Additionally, we used commercial software for RTSim, which allows for a faster adaptation to real applications. As a result, it is straightforward to see how feasible the integration of this type of technology is in a real system.

The rest of the document is organized into five sections. Section II presents the methodological development of the multi-agent scheme (MAS), discriminating the characteristics of each agent using Gaia. Section III explains the IEEE 13 node network modified to operate as MG, the chosen operating scenarios, the selection of protective equipment, and the adjustment criteria. Section IV presents the implementation and results of the protection scheme developed for the modelled MG. Finally, Section V presents the conclusions and discusses future work.

Adaptive Multi Agent Scheme

For the MAS development, we use the GAIA methodology. In this methodology, two phases are used to create a MAS. In the first phase, which corresponds to the power system analysis, the roles and protocols are defined. In the second phase, which corresponds to the design, the agent, the service, and the familiarity models are created [10].

Analysis Phase

In this phase, we describe the roles that will be assigned to each element. Role of measured load (RML), the role of measured distributed generation (RMDG), the role of measured point of common coupling (RMPCC), the role of IED (RIED), and the role of MG intelligent system (RMGIS).

RMDG, RML, and RMPCC describe the connection status of the DG units, loads, and MG, by monitoring switches at the connection points of each element. The RIED monitors the protection, the short-circuit current, and the direction of the current flow. This role is responsible for modifying the protection settings and controlling the operation of the IED.

The RMGIS is responsible for identifying the MG configuration. This role receives information from other roles and sends updated information on the settings and new status of the MG. This role oversees receiving the messages from the measurement roles, analyzing messages, and sending new adjustments to the RIED. This role can read all the connection statuses for the load, generation, and MG, and save the data in a database. It is also responsible for determining the new settings of the relays.

The other protocols define the nature of the interaction between the roles. For example, the RMDG monitors the status of the system generators and sends a message (sender role) to the RMGIS, which in turn processes the connection status of these generators and determines the decisions that need to be taken to update the MG status.

Design Phase

In this phase, we develop the agent models and the service models associated with each agent. We elaborate a collaboration diagram to guarantee a logical operation among the agents and to observe their interactions. Finally, we illustrate the architecture used in the design.

The objective of the GAIA methodology is to determine the roles that need to be created as a set. For efficiency purposes, it is suggested that each role should be assigned to an agent. The service model is the agent's function that specifies the agent's inputs and outputs, whether it has a precondition or if it requires sending a status or message after its function is executed. In this methodology, it is also important to design a familiarity model that details the collaboration between agents and the design architecture. The familiarity model details the collaboration between the agents (Fig. 1), and the architecture of the design (Fig. 2).

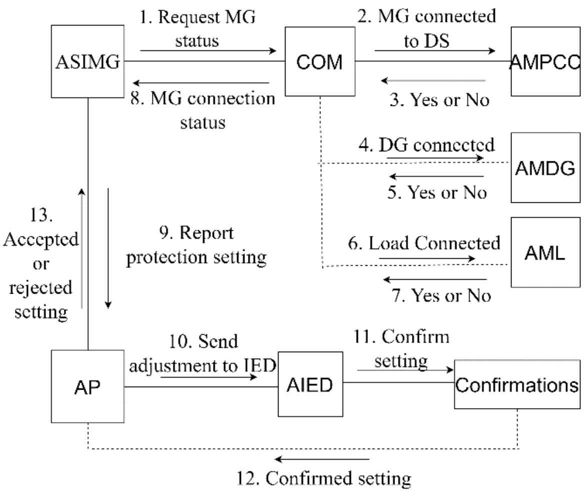


Fig. 1: Collaboration diagram

In the collaboration diagram, there is a measurement agent interface (COM) that represents the graphical interface between the measurement agents and the MG intelligent system agent. Additionally, this agent inquiries from the AMPCC whether the MG has a connection to the distribution system (DS). A protection agent (AP) was also developed to receive updated settings and decide whether to accept them.

The agents and the test case study are connected in the solution architecture. Through communication linkages, the agents get information about the state of the breakers on the DG, PCC, and load, and then the ASIMG defines the new settings that the IED must adopt.

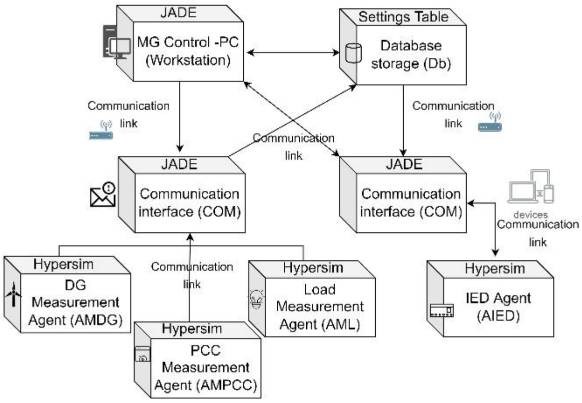


Fig. 2: Solution architecture

Multi-agent Interface

According to the design phase, each agent was created for monitoring and taking action within the network, on the FIPA agent platform, and through the JADE software. Fig. 3 shows an example of the multi-agent interface. Agents have an internal communication system because of the ACL messaging function between agents. Additionally, the IEC 104 communication protocol with TCP / IP is used for communicating JADE and the Hypersim software. Using the IEC 104 library, the connection status of the switch that governs the DG sources and the PCC was identified. Using the MAS algorithm, these connection states were interpreted as zero (0) for disconnected and one (1) for connected. It is identified the appropriate setting for each of the evaluated relays.

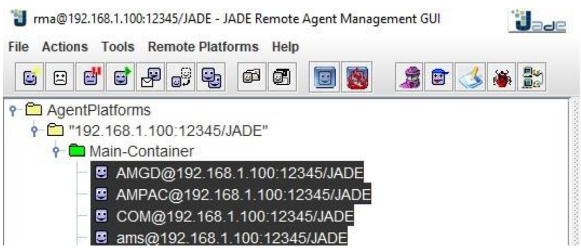


Fig. 3 : Multi-agent interface

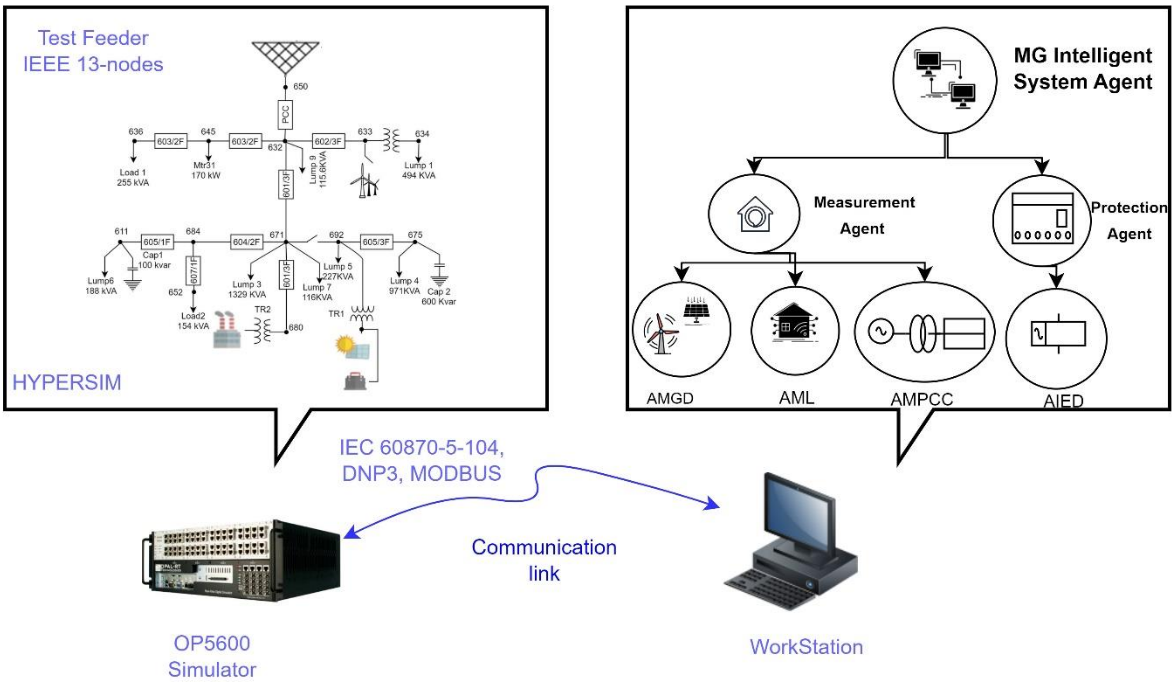


Fig.4: Hybrid architecture of the solution

Study case

The IEEE 13 Node Test Feeder is selected as a case study. This model can be validated simply in a real-time simulator by considering different scenarios and topologies of the MG. Fig. 4 shows the representation of the hybrid architecture of the MG that illustrates the association among the OPAL5600 real-time technology, a workstation, the IEEE 13-node test system modeled in Hypersim, and the MAS developed with JADE.

The MG consists of a solar array with a maximum power of 1 MW, a 1 MW combined cycle plant model, a 1.7 MW type 3 wind turbine, and a lead-acid battery storage system with a maximum power of 1 MW. The total load is approximately 3,515 kW, which is distributed between fixed loads (3,266 kW) and distributed loads (200 kW).

There are two types of loads: a fixed load connected to a specific node, and a distributed or dynamic load connected between two nodes. Fixed loads are considered balanced for all phases and distributed loads are considered unbalanced. There are six Thytronic NA100, NA60, and NA80 protection relays. These Relays are characterized as modular and multifunctional, with access to IEC 104, Modbus TCP / IP communication protocols, and others. One of the relays was located between the MG and the network equivalent, generating a common coupling point (PCC) between the DS and the MG.

Operating scenarios

We selected two operating scenarios: grid-connected MG and grid-isolated MG. The scenarios include the operation of the MG connected to the DS, first with all the available loads without the DER, and second, with all available loads with the DER. Furthermore, we used five topological changes. These are: 1) Normal: Failure in the DS without the DER; 2) DS + MG: Failure in the DS with the integration of the MG; 3) MGConnectedSW: Failure in the MG connected to the DS when the solar generator and wind generator are operating; 4) MGConnectedWCHP: Failure in the MG connected to the CHP and wind generator; 5) MGConnectedSCHP: Failure in the MG when it is connected to the DS and the solar generator, and the CHP are operating-

Selection of the protection and adjustment criteria

We selected a directional overcurrent protection relay (DOCR). This is one of the most widely used device for adaptive protection schemes. This is due to its directional capacity, which allows the detection of a change in the power flow direction that occurs with the insertion of an MG. In addition, the DOCR is flexible, reliable, and efficient in MG protection.

For the coordination of the protection relays, the instantaneous pickup was set to adjust with a value between 1.02 and 1.05 times the maximum short-circuits current of the protection zones [11], and the time for coordination between the relays was set to 0.2 sec.

Implementation of the protection scheme

In this section, we describe the proposed protection scheme implementation. First, we present the relay locations and their normal mode settings. Second, using three-phase faults, we show the relay selectivity and operation in the system. Third, we show the integration of the real-time software with the multi-agent algorithm.

Proposed location of protective equipment

Six directional overcurrent relays, Rmain, and R1-R5 are included in different sections of the system to protect the necessary areas for the proposed MG, as shown in Fig 5. We conducted load flow and short-circuited studies to determine the measurement equipment needed and the protection adjustments under normal operating conditions of the MG.

Adjustment and coordination of protections – offline analysis

We used the nominal current to determine the values of the current meters for each relay in the system, as illustrated in Table I. After the selection of the CTs, the protection coordination is conducted using the STAR module of the ETAP 19 software. Table I shows the resulting pickup values and delay time for the instantaneous overcurrent protection (50) and the pickup values and dial current of the time-delayed overcurrent protection (51).

Protection selectivity and operation

We simulated a three-phase fault in the first circuit's tail (Zone 1), the red zone in Figure 5, to assess the selectivity and performance of the integrated relays. We observed that the proposed protection scheme is selective.

for the tested network. According to the results, R1 operated at 30 ms, R2 operated at 237 ms, and Rmain operated at 2220 ms, guaranteeing adequate protection coordination in the fault zone.

Similarly, we simulated the same type of three-phase fault in Zone 2. The results show that the relay R3 operates first at 30 ms, followed by R4 and R5 which operate at 240 ms and 456 s, respectively. This result guarantees an adequate protection coordination in the corresponding fault zone.

Using the same protection scheme and settings, we run the same simulations but with DER. We observed a variation in the relay adjustment times that affected their coordination. As a result, this required modification of the relay setting, as shown in Table II

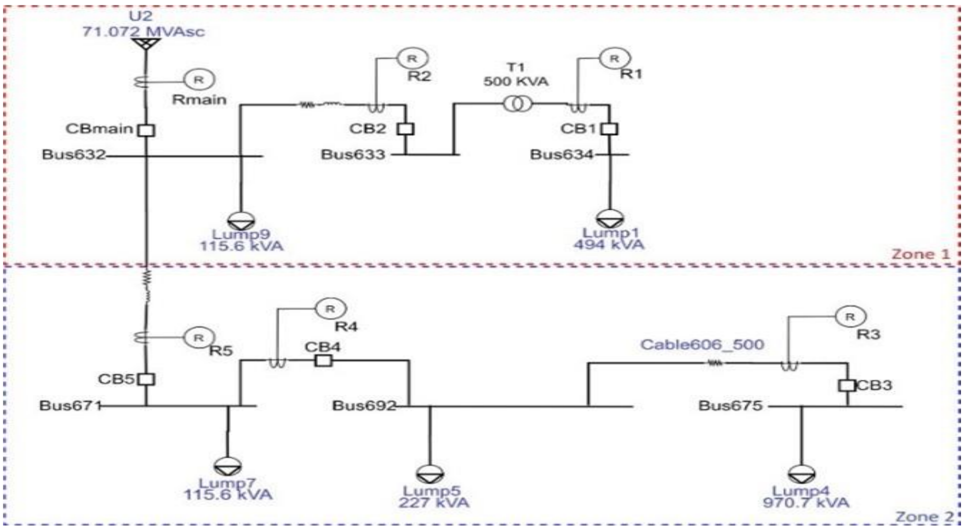


Fig 5: Relay location

Table I : Consolidated Settings 50/51 – DS Connection Type

Relay	Node	CT	ANSI/IEEE	Instantaneous protection setting (50)		Time-delayed protection setting (51)	
				Pickup	Delay	Ipickup	dial
Rmain	632	600:1	VI	4932	0.03	1.077	3.72
R1	633	1200:1	VI	10067	0.03	0.493	1.87
R2	634	500:1	VI	4282	0.03	0.171	1.04
R3	671	400:1	VI	2686	0.03	1.159	1.16
R4	675	300:1	VI	3025	0.03	0.49	0.45
R5	675	300:1	VI	3025	0.03	0.49	0.45

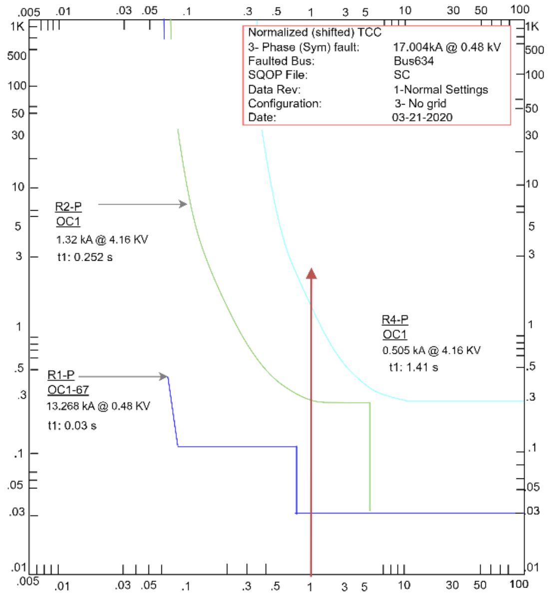
We run the same simulations but isolate the MG from the DS. We kept the same adjustments seen in Table II and proceeded to evaluate the selectivity of the protections against the fault in the tails of the circuits of Zone 1 and Zone 2. In Fig 6, panel A, we can see how before a fault occurs in Zone 1, R4 protection, located in Zone 2, enters operation.

In Fig. 6, Panel B, we can see the fault behaviour in Zone 2, in this case, the R2 protection, located in Zone 1, enters in operation at 352 ms. This unwanted tripping is owing to the contribution of the fault current by the connected DG sources in Zones 1 and 2.

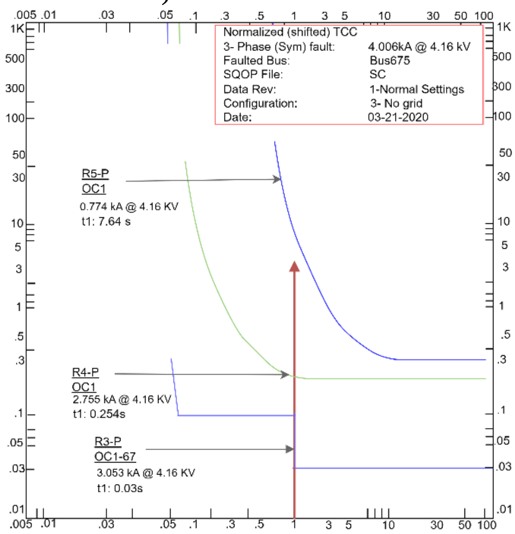
To summarize, unexpectedly, protections R4 and R2 tripped under the integration of DER in response to a fault in Zone 1 and Zone 2, respectively. The above procedure is performed for the isolated MG. It was observed that the short-circuit levels decrease when the MG is disconnected from the DS. Likewise, these short-circuit levels vary with the type of generation source operating in the system. The MG operation protection times must be adjusted according to the type of generation.

Table II : Consolidated Settings 50/51 – DS Connection Type + DER

Relay	Node	CT	ANSI/IEEE	Instantaneous protection setting (50)		Time-delayed protection setting (51)	
				Pickup	Delay	Ipickup	dial
Rmain	632	600:1	VI	4932	0.03	0.24	6.8
R1	633	1200:1	VI	10291	0.03	0.49	0.78
R2	634	500:1	VI	4443	0.03	0.31	2.38
R3	671	400:1	VI	3398	0.03	0.37	0.02
R4	675	300:1	VI	3771	0.03	0.23	2.71
R5	675	300:1	VI	2737	0.03	0.52	4.86



a) Panel A - Zone1



(b) Panel B – Zone 2

Fig 6. Relay operation curves for a fault in (a) Zone 1 and (b) Zone 2.

Evaluation of the operation of the protections in RTSim - online analysis.

We proceeded to create in the OPAL RT Hypersim software, the MG selected to be evaluated in RTSim, as shown in Fig 5. Using the SIL configuration of RTSim, we performed a simulation of the directional overcurrent relay (50/51/67) in the simulated network by introducing a symmetric short-circuit fault in Zone 1 and validating the results of the operating sequence, short currents, and trip times (see Fig. 7).

As Fig. 7 shows, we observed selectivity and coordination in the operation of the relays. Protection R1 opened first (closest to the fault) at 31 ms, then R2 at 229 ms, and finally Rmain at 1107 ms. After connecting the DER and simulating the same type of fault in the tail of Zone 1, we observed that under the fault event in bus 1, protection R2 operated before the start of the fault in response to an overload that triggered the timer. Next R1 and Rmain entered in operation at about 450 ms and 1770 ms, respectively. This illustrates how renewable integration can modify the nominal currents in each relay and cause the loss of selectivity and coordination.

As mentioned in section 3, when the MG is connected to the DS (MG1), the algorithm we used is the MAS which defines the settings that must be modified.

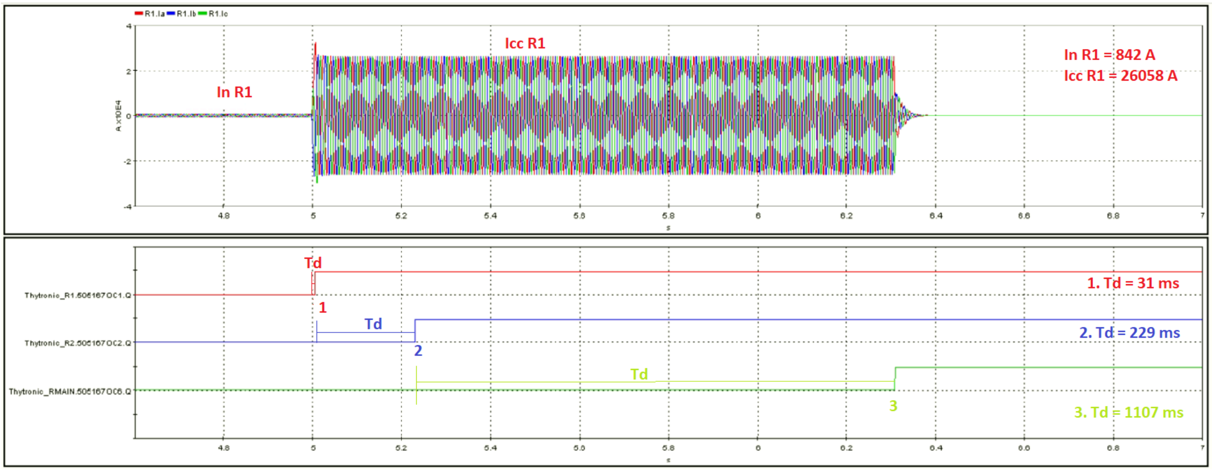


Fig 7. Operation sequence, short circuit currents, and tripping times for a fault in Zone 1.

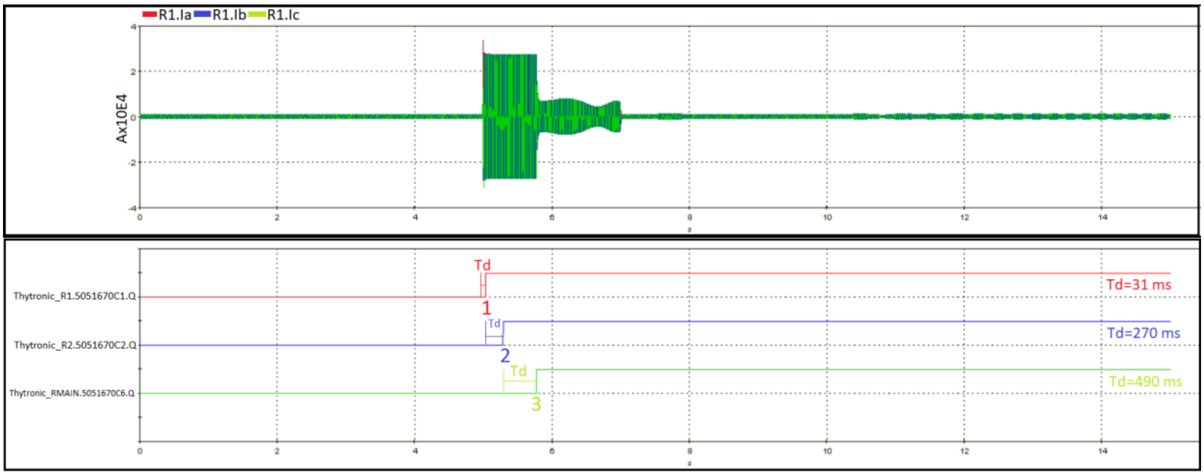


Fig. 8: Operation sequence, short-circuit currents, and trip times for a fault in Zone 1 with a change of settings.

In summary, the integration of renewable energy sources leads to modifications of the time settings of the relays.

As shown previously, when the MG is connected, the normal network settings do not allow selectivity and coordination to be achieved. Fig. 8 illustrates the responses obtained after including the new settings from the adaptive algorithm in the relays.

The graph illustration is twofold. First, it shows that R1 operates at 31 ms, followed by R2 and Rmain, which operate at 270 ms and 480 ms, respectively. Second, it illustrates that R2 operates after the failure occurred, guaranteeing selectivity and coordination.

Finally, when the MG is disconnected from the DS (MG0), the MAS identifies the connection status of the DG and sends a message indicating the setting of each of the relays. However, according to the type of connected renewable sources, reductions in short-circuit current levels are observed. This implies that to guarantee that the relays operate selectively, it is necessary to create a matrix of adjustments for each type of configuration. It is important to note that the simulation of the MG when it is disconnected from the DS was carried out with the ETAP RT software.

Conclusion

In this paper, we developed a multi-agent adaptive protection scheme using six (6) directional overcurrent protections in different zones of an MG and designed five (5) agents that determine the network topology and define the new adjustment of the required protections. Moreover, we validated the protection scheme operation for the selected MG using the ETAP-RT software and show how the protection settings

under a normal operation scenario, i.e., without integration of distributed resources, must be adjusted when including the MG.
In addition, we demonstrated that the protections could not operate selectively when keeping the same adjustments when there is a topology change or when we isolate MG. Furthermore, when using the RTSim, due to its evaluation in the time domain, we observed a timing mismatch due to the inclusion of GD, which did not occur in the ETAP RT software. We also showed that the MAS guarantees the selective protection of the MG by establishing the new settings for the system relays.

In summary, the development of decentralized adaptive schemes will provide more dynamic protection. However, to achieve the correct operation of these protections, artificial intelligence is required to guarantee adequate decision-making, operational autonomy, and adequate monitoring and diagnosis of faults. In turn, establishing the reliability of these systems requires additional RTSim tests, including those of the communication systems used.

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