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RESEARCH ARTICLE

Balancing Decentralization for Restoration in Power Distribution Systems With Agents

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ABSTRACT Power distribution systems are subject to faults that may cause service interruptions. The outage impact can be attenuated by restoration procedures, aiming to reconfigure the grid until faulted components are repaired. Proposals for these procedures are usually either fully centralized or fully decentralized. In this paper, a hybrid approach (partially decentralized) for the restoration problem based on a multi-agent system (MAS) is proposed and evaluated. Results show that caution must be taken when specifying the level of decentralization achieved by agent based procedures devoted to system restoration, especially if low power devices are utilized to achieve agent communication.

INDEX TERMS Decentralized power restoration, self-healing grids, multi-agent systems.

I. INTRODUCTION

In power distribution systems, restoration processes are implemented to minimize the number of interrupted customers and/or load during network repair. Solutions for the restoration problem are based on executing a set of control actions in which a combination of switching operations are determined. The resulting problem usually becomes considerably large to be optimally solved given the system size as well as aspects related to system expansion, system modernization and attribution of load priorities.

In the literature, methods to address the restoration problem are usually either fully centralized or fully decentralized. In the former, all data required to solve the problem is collected in a central point where a solution is specified. Heuristic based approaches are commonly used (e.g., genetic algorithms [1]) since the formal calculation of a global optimal solution is not computationally feasible for (some) large networks. Moreover, all processes executed at the central point must have high levels of availability and robustness due to the deployed hierarchical structure. In decentralized solutions, on the other hand, there is not a unique central point of decision making and each device (e.g., switch, recloser) has some autonomy on deciding locally whether to change its state based on data acquired through local sensing and communication.

In this context, this work provides, as contribution, an agent based approach to system restoration using the block concept [2], [3] and investigates the impact of the level of decision-making block decentralization on system reliability. In the approach, a block represents a sub-network of the electric grid and is autonomously managed by a software agent. The level of influence of a block corresponds to the number of switching devices in this sub-network. If the

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level of influence of all blocks is one, we have a fully decentralized restoration system; if there is only one block for the whole system, we have a centralized restoration system, at least in the block concept sense, though some decentralization from decision making at control centers can be still considered as achieved. Each block agent negotiates alternative supplies with neighbors and then decides whether to open or close its switches based on an algorithm applied only in its own context. Agent simulation follows an Agents & Artifacts approach [4], envisioning the embedding of the agent in a low cost recloser equipment, developed under the framework of a R&D project, with integrated current sensor and voltage presence detector. Case studies assume, for the communication process, the usage of IPv6 over the Time-Slotted Channel Hopping (TSCH) mode of IEEE 802.15.4e (6TiSCH), which offers flexibility due to its mesh topology. Results with the IEEE 123 node test feeder show that caution must be exercised when specifying the level of decentralization achieved by agent based solutions designed to distribution system restoration.

II. RELATED WORK

In the last few years, many approaches using MAS have been proposed in the technical literature to solve the restoration problem. The work in [5] proposes an approach to restore critical loads in distribution systems with distributed energy resources through a decentralized MAS framework with peer-to-peer communication, aiming to maximize the reliability of the restoration plan and decrease the chances of post-restoration failures. The work in [6] evaluates the restoration problem in a smart distribution system through objective functions that aim the maximization of restored loads and the minimization of switching costs. A MAS architecture is applied to isolate the fault, shed or restore loads and to change the system topology. A fully decentralized MAS has been presented in [7] for self-healing control, where an integrated multistage strategy is addressed with decision-making agents and tasks which change dynamically according to stages as, for example, when there is a transition from the normal to the abnormal communication stage.

Some works implement their MAS using JADE (Java Agent DEvelopment framework) as a mean to test their approaches. As examples, the authors in [8] propose an approach where it is possible to take load priority in the restoration process; and [9] also takes into consideration the limits of the distributed generations and of the distribution lines.

Hybrid solutions are less common, but considered in [10] where the authors mention the difficulty of operating purely centralized solutions and opt for a strategy where an agent in the distribution feeder is responsible for the restoration process using both voltage and current phasors, and agents placed alongside the feeder must isolate the fault. Some works also propose solutions capable of locating the fault in the distribution system, where the usage of synchrophasors (phasors synchronized in time) allows for the MAS to find the agent in the boundary of influence of a fault through current signals [11] or angular difference [12].

In [13] the authors propose a decentralized technique for the restoration problem considering voltage restriction and current line limitations. Although part of the processes is decentralized, the restoration is decided by a single agent at the zone where the fault occurs. In [14], a MAS is implemented to solve the restoration problem in a distribution system conceiving four different type of agents. As in [13], the restoration is tackled by a single feeder agent which requests other switch agents to open or close their switches accordingly. A MAS restoration method considering six different types of agents and uncertainties of load and DGs (Distributed Generators) is proposed in [15]. In this work the main objective is to maximize the restoration of priority loads and minimize the number of switch actions.

In [16], an approach for for the restoration of distribution systems is proposed using the IEC 61850 communication protocol for fast relays responses. Their main objective is to restore the maximum number of customers with the minimum amount of switching. In the proposed methodology, two layers of agents are implemented and the restoration problem is solved by an agent that runs in a computer outside of the feeder.

The works in [5]–[19] are based on the principle of decentralizing decision making by deploying agent systems' principles. A large variety of agent types and decision making structures are used. Also, the separation of the agent and environment layers are not deployed explicitly in simulations. Even though all related works tackle the restoration process for distribution systems using MAS, they do not address the application of the block concept alongside the search for a balance between centralization and decentralization within the structuring process of the MAS architectures. This type of analysis is facilitated by the application of the Agents & Artifacts approach, where there is an explicit separation of the agent and environment layers.

III. AGENT AND BLOCK MODEL

Inspired by [2], [3], we model the distribution system dividing it into blocks with their corresponding agents. The block agent is responsible to automatically reconfigure the source of energy as soon as possible after the moment that a fault is isolated. This process aims to reduce the number of affected consumers and consists of (1) finding out new sources of supply; (2) changing the state of the block switches to reconfigure the network based on different energy sources; and (3) returning the system to the normal state when the faulted section is repaired.

The number of switching elements/reclosers in each block (its *size*) can be chosen based on different aspects such as different regions of a feeder, different feeders at the same region, different necessity of control, communication distance limitations, and others. An example of a system

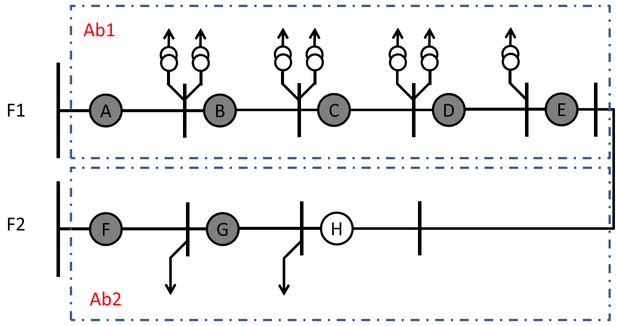


FIGURE 1. RBTS BUS2 F1 and F2 modeled as two blocks.

TABLE 1. Information available in recloser artifacts.

Information	Type	Description
Voltage presence	Boolean	True if there is voltage in the sensing side of the recloser
Switch Open	Boolean	True if the device is open
Lockout	Boolean	True if the device is locked and cannot be operated by another agent (e.g., device opened due to a protective maneuver)
Live Line	Boolean	True if there is a maintenance crew working on the grid
Current	Float[]	RMS current in each phase of the device, used by the agent to estimate load
Neighbors	String[][]	identification of linked recloser, both upstream and downstream
Normal	Boolean	True if the normal operation (i.e., no fault circumstance) of this recloser is open

where T[] indicates an array of type T

modeled as blocks is shown in Fig. 1: the RBTS-BUS-2 feeders F1 and F2. In this example the system has two blocks: one for F1 and another for F2 [20]. Circles are switches (reclosers) equipped with overcurrent relays — empty and filled circles represent open and closed switches, respectively. In this example the block agent 1 (referred as `ab1`) is responsible for the supply from F1 and controls reclosers A, B, C, D and E. Block agent 2 (referred as `ab2`) is responsible for the supply from F2 and controls reclosers F and G. The recloser H is considered a neighbor switch and can be controlled by both `ab1` and `ab2`.

Our implementation of this agent and block model is based on the Agents & Artifacts approach [4] available in the JaCaMo development tool [21]. Agent related information is represented in symbolic form by predicates, as described in [22]. In this approach we clearly distinguish the active part of the system (the agents) and the passive part of the system (the artifacts). While agents are responsible for decisions, artifacts are used to represent the plant of the MAS. The set of all artifacts composes the environment that is perceived by the agents and where they may act. In the case of our restoration system, each block has an assigned responsible agent and a set of artifacts representing the block switches (or reclosers). Summarily, we implement block reconfiguration strategies in the agents and the integration with the real and concrete plant in the artifacts. In the next sub-sections, details of these two parts are provided.

A. ARTIFACT MODEL

The information provided by each artifact is described in Table 1. The artifact also provides operations to open, close, and lock out its recloser. Besides the reclosers state, a block agent also has information about the grid configuration and its position related to other blocks:

id : each block agent has a unique identification used to communicate with other agents (e.g., `ab1` in the case of the agent of the upper block in Fig. 1).

block reclosers : a list of recloser identifications that belongs to the block (e.g., `[a,b,c,d,e,h]`).

neighbors agents : a list of neighboring blocks together with their agents and linking recloser (e.g., `[(ab2,h)]`).

priority list : a list of priority areas inside the block (like hospitals), these areas have to be restored first in case of limited amount of alternative supplies (e.g., `[c,d,e,a,b]`).

feeder connection : a list of feeder connections in the block and their capacity (e.g., `[(f1,110)]`).

Agents can observe and react to changes in the artifact attributes following the Agents & Artifacts model.

B. AGENT MODEL

The decentralization of the system is based on the fact that every block agent runs independently of others, taking decisions based on local information, focused on the utilization of a low cost recloser equipment, developed under the framework of a R&D project, with integrated current sensor and voltage presence detector. A block agent has three essential goals to achieve: handle local faults, help neighbors with their own faults, and return to normal operation. For the first goal, whenever an agent perceives that one of its reclosers was open due to a fault, the following steps are executed:

1) isolate the faulted area of the block by opening and locking the reclosers in the faulted section;
2) open all reclosers without voltage;
3) start a self-healing process (restoration within the block) and try to restore itself on the basis of inner alternative sources of supply; If inner alternative sources are not available, the agent negotiates with neighbors an alternative supply.
4) if an alternative is found (either from a local source or a neighboring block), it runs Algorithm 1 to search for the optimal set of reclosers to close;
5) finally, it closes the appropriate reclosers as to reconfigure the block.

As an example, consider a fault between reclosers B and C in the system depicted in Fig. 1. As a reactive procedure of its protection relays, recloser B will trip automatically causing the block agent *ab1* to start the restoration process described previously. The agent will open and lock recloser C in step (1) and then open reclosers D and E without locking them in step (2). To mitigate the impact of the fault, it will negotiate with agent *ab2*, its neighbor, an alternative and sufficient supply of P kW (step 3). When the negotiation is positively cleared, it will close reclosers H, E, and D, in this order, one by one.

In this example, the Algorithm 1 is called as `reconfig(h,k,[d,e])`. The third argument is the priority list of the block without the isolated (`[b,c]`) and not affected areas (`[a]`). The algorithm basically verifies if {`h`} can be supplied by k, if so, it verifies if {`h,d`} can also be, and finally, it verifies if {`h,d,e`} can be supplied; i.e., the priorities are being added in the solution set one by one. The boolean function *BFS*, based on the Best First Search [23], verifies if a set g of reclosers can be supplied by k from f. In the BFS, a state $s \in O$ is a set of possibly closed switches. The time complexity of this algorithm is exponential, thus the designer has to carefully specify the number of focused artifacts.

The second goal consists basically in promptly answering when neighbors ask for an alternative supply as defined in step (3) and as detailed in Sec. III-C.

For the third goal, when the field crew have repaired the faulted branch, the system can be brought back to the normal operation state following the steps described below:

1) open all reclosers that are normally open and are currently closed;
2) wait for all agents affected by the fault to finish the previous step;
3) open all closed reclosers with absence of voltage signal;
4) wait for all agents affected by the fault to finish the previous step;
5) close all reclosers that are normally closed.

Considering the above example, in step (1), the agent opens recloser H; in step (2), there is nothing to do since only `ab1` was affected by the fault; in step (3), it opens C, D, and E; in step (4), there is nothing to do as well; and finally, in step (5), it closes A, B, C, D, and E, in this order. As it occurs in the restoration process, the agent closes each recloser only when the previous one is already closed, aiming to reduce inrush currents and to avoid meshed/ring operation.

This process requires a coordination between the actions of the agents. All agents affected by the fault have to finish step (1) before starting step (3) and similarly for step (5). Some distributed synchronization is thus required. We implemented this by electing the agent located where the fault occurred as the coordinator. It sends messages to the other agents asking them to execute step (1), waits for them all to send confirmation and only then moves to step (3) and so on.

Algorithm 1: Block Reconfiguration Algorithm

```
Function reconfig($f, k, p$)
Input: $f$: first recloser; $k$: available energy; $p$: priority list;
Output: list of reclosers to close
Data: $e(\cdot)$: the energy necessary for a recloser area
if $e(f) > k$ then
    return {}
$c \leftarrow \{\}$                    //set of current served areas
$a \leftarrow \{\}$                    //current best solution to serve c areas
for $r$ in $p$ do
    $t = BFS(f, c \cup \{r\}, k)$      //try to add r
    if $t \neq null$ then
        $c \leftarrow c \cup \{r\}$
        $a \leftarrow t$
return $a$
Function BFS($f, g, k$)
Input: $f$: first recloser; $g$: set of target reclosers; $k$: available energy;
Result: whether all reclosers in $g$ can be closed
$O \leftarrow \{\ \{f\}\ \}$    //a state is a set of reclosers candidate to close
$g[f] \leftarrow e(f)$    //$g[\cdot]$ is the required energy to achieve a recloser
while $O \neq \{\}$ do
    $s \leftarrow remove(O)$
    if $g \subseteq s$ then
        return $s$
    else
        forall $r$ in $s$ do
            forall $r'$ linked to $r$ do
                $g[r'] \leftarrow g[r] + e(r')$
                if $g[r'] \leq k$ then
                    $O \leftarrow O \cup \{\ s \cup \{r'\}\ \}$
return $null$
```

C. NEGOTIATION

Contract Net Protocol (CNP) [24] is used by the block agent to find another energy source to restore the supply of affected (but not faulted) zones in its block. In this protocol, an agent desires to contract a service or buy a product and adopts the role of initiator. Agents able to provide the service play the role of participants (see Fig. 2). In the restoration problem, the agent that needs an alternative source of energy plays initiator and its neighbors play participant. The initiator starts the protocol by sending a "call for proposal" (`cfp`) to participants with its load demand, estimated using the load current. A participant may answer with a proposal (if it can help) or a refusal message (otherwise) depending on whether or not the agent has a connection with an alternative energy supply. The participant proposal is computed based on the block surplus (energy available in its feeders minus its local requirements). The initiator selects the proposal that better fulfills its request of power demand.

In case the CNP fails, the agent waits some time and tries again later. This is necessary when its neighbors have refused

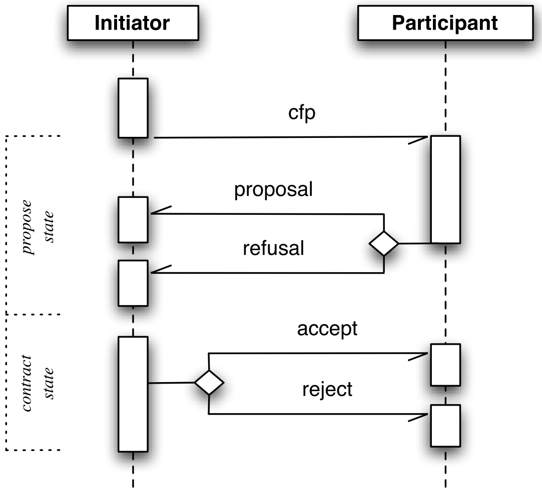


FIGURE 2. Contract net protocol.

to help because they are equally without supply, but may be negotiating (also with CNP) an alternative source further away. If later a neighbor finds a solution with surplus, it may answer with a proposal to help the former agent.

IV. EXAMPLE

For this section, the distribution system shown in Fig. 3 is used to further exemplify the proposed restoration process [18]. It has three different power supplies: F1 is the main power source of the system, while F2 and F3 feeders belong to another feeder system. In the three feeders, a total of 13 reclosers are connected throughout the network. In order to avoid meshed/ring operation, reclosers identified by G and K must remain open in normal operating state. In the diagram, dashed lines delimit blocks, reclosers are positioned as shown with the voltage detection side indicated by a red circle, and arrows represent spot loads. For this example unlimited transfer capacity is considered in all three sources.

Fig. 4 contains a sample of the information available for the agent (identified as `ab1`) responsible for the first block. This information comes from the artifacts of the block and, in JaCaMo, it is represented as an atomic formula of first order logic and conceived as beliefs [4]. As exhibited in the figure, the normal operation of each recloser and its actual state are the same, implying that the block is in the normal operation state. The equipment D and I are neighbor reclosers connecting block 1 with blocks 2 and 3, respectively.

In this example we consider a fault in the branch between reclosers A and B that automatically opens recloser A. This event is perceived by the agent `ab1` as a change in its beliefs:

```
switch("open")[artifact_name(_,recloser_a)].
```

Using the proposed approach for the restoration process, the steps taken by the MAS are the following:

1) Agent `ab1` opens recloser B and performs lockout in reclosers A and B, isolating the faulted section.

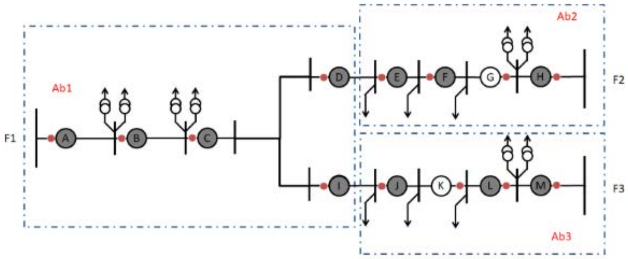
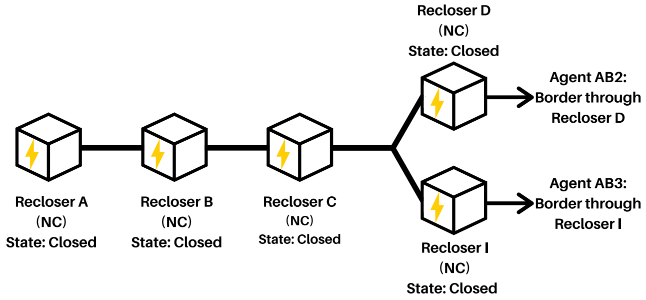


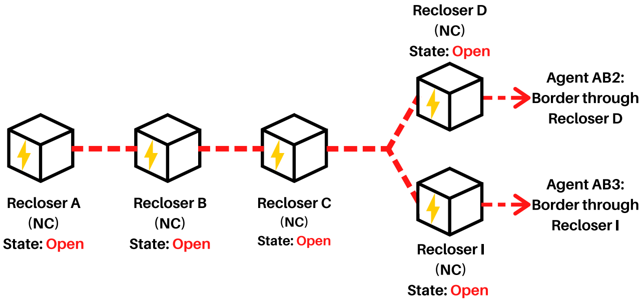
FIGURE 3. Example plant.



```
normalOperation("closed")[artifact_name(_,recloser_a)].
normalOperation("closed")[artifact_name(_,recloser_b)].
normalOperation("closed")[artifact_name(_,recloser_c)].
normalOperation("closed")[artifact_name(_,recloser_d)].
normalOperation("closed")[artifact_name(_,recloser_i)].
switch("closed")[artifact_name(_,recloser_a)].
switch("closed")[artifact_name(_,recloser_b)].
switch("closed")[artifact_name(_,recloser_c)].
switch("closed")[artifact_name(_,recloser_d)].
switch("closed")[artifact_name(_,recloser_i)].
rel_border(ab2,recloser_d).
rel_border(ab3,recloser_i).
```

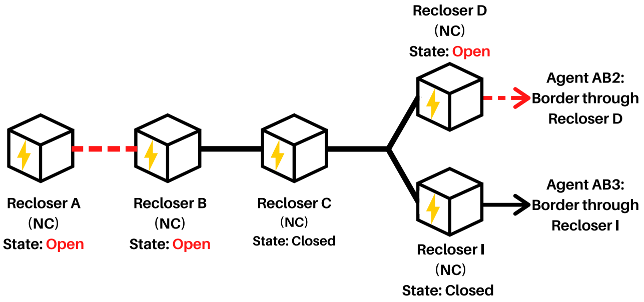
FIGURE 4. Agent `ab1` block state in normal operation and the corresponding beliefs (NC means normally closed).

2) Due to the absence of voltage, `ab1` opens reclosers C, D and I. Similarly agent `ab2` opens reclosers E and F and agent `ab3` opens recloser J. Fig. 5 contains the mind state of `ab1` after the fault.
3) Agent `ab2` verifies that recloser D has opened due to the action of another agent. Since `ab2` has an available feeder and a disconnected area without faulted sections, it checks the possibility of rearrangement within its own block. Thus, `ab2` closes recloser G, F and E. As equipment D is shared with `ab1` (a boundary recloser), `ab2` does not close it at this stage. Likewise, agent `ab3` checks for disconnected areas in its block and the possibility of reconfiguration. It therefore closes reclosers K and J.
4) Agent `ab1`, which does not have alternative feeders, starts the negotiation with its neighboring agents `ab2` and `ab3` by sending them a *call for proposal* message.
5) Agents `ab2` and `ab3` receive the message from ab1 and verify the possibility of supplying the requesting block. Considering they have enough transfer capacity, estimated using the sensed current and network data, they send a proposal to `ab1` with the available transfer capacity.



```
normalOperation("closed")[artifact_name(_,recloser_a)].
normalOperation("closed")[artifact_name(_,recloser_b)].
normalOperation("closed")[artifact_name(_,recloser_c)].
normalOperation("closed")[artifact_name(_,recloser_d)].
normalOperation("closed")[artifact_name(_,recloser_i)].
switch("open")[artifact_name(_,recloser_a)].
switch("open")[artifact_name(_,recloser_b)].
switch("open")[artifact_name(_,recloser_c)].
switch("open")[artifact_name(_,recloser_d)].
switch("open")[artifact_name(_,recloser_i)].
```

FIGURE 5. Agent `ab1` block state after fault and the corresponding beliefs.



```
normalOperation("closed")[artifact_name(_,recloser_a)].
normalOperation("closed")[artifact_name(_,recloser_b)].
normalOperation("closed")[artifact_name(_,recloser_c)].
normalOperation("closed")[artifact_name(_,recloser_d)].
normalOperation("closed")[artifact_name(_,recloser_i)].
switch("open")[artifact_name(_,recloser_a)].
switch("open")[artifact_name(_,recloser_b)].
switch("closed")[artifact_name(_,recloser_c)].
switch("open")[artifact_name(_,recloser_d)].
switch("closed")[artifact_name(_,recloser_i)].
```

FIGURE 6. Agent `ab1` block state after restoration and the corresponding beliefs.

6) Agent `ab1` receives the messages from both neighboring blocks and selects the best proposal. Considering that the proposal from `ab3` is better according to a specified criterion (e.g. higher transfer capacity), `ab1` accepts the help from agent `ab3` and sends a new message to the agent confirming that it will close the boundary equipment between the two blocks (i.e., recloser I).
7) Agent `ab1` runs the optimization algorithm considering its priorities and the amount of energy provided by `ab3`. After optimization, the result of the algorithm is to close I and C. Equipment A and B are locked and will not be restored.
8) Agent `ab1` first closes recloser I and then recloser C. Fig. 6 contains the mind state of `ab1` after the restoration process: there are three open reclosers: A and B, due to the lockout, and D, the neighbor recloser with block 2.

The steps to return the grid to normal operation are described below:

1) The field crew repairs the faulted section between reclosers A and B and informs the distribution system operator that the system can return to its normal operation. The operator then sends a message to the multi-agent system to start the procedure.
2) Agents `ab1`, `ab2` and `ab3` initiate in parallel the process of returning to the normal operation by opening reclosers which are normally open. Since `ab1` does not have any normally open reclosers, no action is performed. Agent `ab2` opens the recloser G while `ab3` opens recloser K. Shortly thereafter, they send a message to `ab1` stating that they have completed the first step.
3) When `ab1` receives the message from `ab2` and `ab3` that they have finished the previous step, `ab1` starts opening reclosers without voltage presence: reclosers C and I. Agent `ab2` opens reclosers E and F, while `ab3` only opens recloser J. Again, `ab2` and `ab3` inform `ab1` when they have finished this step.
4) Agent `ab1` starts to close locked reclosers that are normally closed, that is, reclosers A and B. Since no equipment is locked in blocks 2 and 3, agents `ab2` and `ab3` have nothing to do.
5) Finally, `ab1` initiates the closing of normally closed equipment, closing reclosers C, D, and I, in this order, as the presence of voltage is perceived in each equipment. Then, `ab2` closes E and F, while `ab3` closes J.

V. EVALUATION

The proposed approach has been applied to the IEEE 123 node test feeder. The IEEE 123 test feeder has a total load demand of 3,490 kW and a 4.16 kV nominal voltage. The substation transformer of the system has a 5 MW nominal capacity. For the analysis of the system, each switch is considered as a low cost recloser and 5 more equipment have been implemented as shown in [25].

Our analysis focuses on assessing the system reliability considering the proposed MAS restoration process. We assume that each customer has a 0.5 kW of load demand and a total of 6,980 customers are connected to the feeder. In this analysis, a single line representation is used and, for the reliability evaluation, four different cases are considered:

- Case 1 (C1): The system has no agents and thus no restoration process occurs.
- Case 2 (C2): The system has 1 block with assumed unlimited transfer capacity;
- Case 3 (C3): The system has 3 blocks with assumed unlimited transfer capacity;
- Case 4 (C4): The system has 8 blocks with assumed unlimited transfer capacity;

For cases C2, C3 and C4, we consider that, in the communication process, each hop between the source and the destination increases the latency by 2 s. Noting that the 6TiSCH divides the time in *slotframes*, and that each

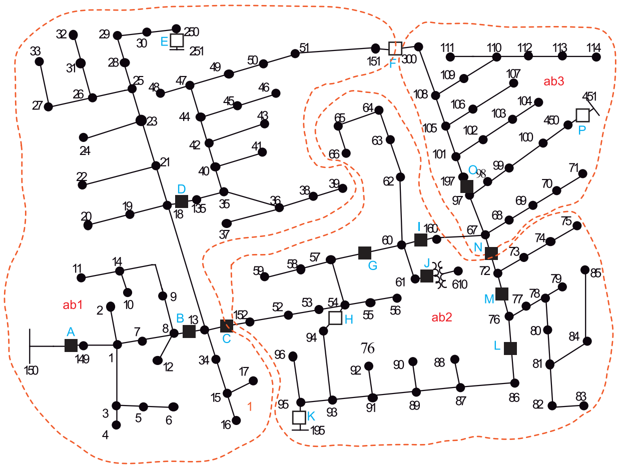


FIGURE 7. IEEE 123 nodes test system divided into 3 blocks.

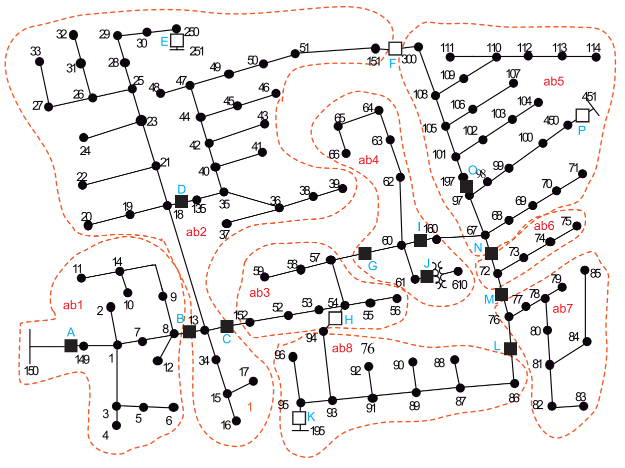


FIGURE 8. IEEE 123 nodes test system divided into 8 blocks.

TABLE 2. Optimization cases.

Case	SAIFI [occ/yr]	SAIDI [h/yr]	ENS [kWh/yr]	CAIDI [h/occ]
C1	2.5975	10.3902	36,944.1972	4.00
C2	2.5075	2.9352	9,979.8260	1.1705
C3	1.0517	2.8173	9,545.5328	2.6787
C4	0.7028	2.8111	9,524.6948	4.00

slotframe is composed of 101 slots of 0.04 s in which pairs of nodes are able to communicate, the 2 s latency assumption is equivalent to conveying 2 messages per *slotframe*. Such assumption is in accordance with [26], in which the latency associated with each hop was between 2 s and 2.7 s for a network with uniformly randomly generated node positions. The reliability metrics used for the analysis are: SAIFI (System Average Interruption Frequency Index), SAIDI (System Average Interruption Duration Index), ENS (Energy Not Supplied), and CAIDI (Customer Average Interruption Duration Index). Details about these reliability metrics can be found in [27], [28].

Fig. 7 and Fig. 8 shows the IEEE 123 test feeder for C3 and C4, respectively, with its corresponding recloser placements. Black squares are normally closed equipment and white squares are normally open equipment. Each block and equipment is named in the figure. As exhibited in Fig. 8, the block size varies from agent to agent; we have thus large blocks (e.g., `ab2`) and small blocks (e.g., `ab7`) in the same distribution system without loss of generality. For C2, the block agent is considered embedded in recloser A, near the substation. In C3, the block agent `ab1` is embedded in recloser A, `ab2` in recloser G, and `ab3` in recloser O. For C4, block agent `ab1` is embedded in recloser A, `ab2` in recloser D, `ab3` in recloser G, `ab4` in recloser I, `ab5` in recloser O, `ab6` in recloser N, `ab7` in recloser L, and `ab8` in recloser K.

Table 2 contains the reliability results for all cases. The considered failure rate and repair time are 0.5 occ/(yr·km) and 4 h/occ, respectively, for all branches. Sustained interruption is assigned if the period that a customer service is interrupted is higher than one minute [29].

For the base case (C1), we have that the mean time that customers are not supplied is close to 10 hour/year. One important distinction to be made is that, because the SAIDI metric is an average of customer interruption durations throughout the system, certain branches will have higher values. For example, all nodes that are downstream of node 76 (south-east of the system) will have local unavailabilities of 16.75 h/yr as all permanent faults in the main trunk will end up affecting them.

The outcomes of case C2 highlights that the consideration of communication delay between agents has a direct impact on the metrics: CAIDI, SAIDI and ENS are lower than in the first case. In C2, restoration processes are only faster than 1 minute for faults downstream of reclosers M and N due to communication latency. For the CAIDI, SAIDI and ENS indices, even though the restoration is not fast enough to avoid sustained interruptions, the period in which customers are unserved during a year decreases 3.5 times in average in comparison to the base case.

For the case with 3 block agents (C3), it is possible to notice that the MAS increases the reliability of the system: the SAIFI and SAIDI metrics have an improvement of roughly 65% and 75%, respectively. For this case, only faults at the middle of the feeder have restoration times higher than one minute. As we have customers with sustained interruption periods closer to one minute at restored branches and 4 hours for interrupted branches, the CAIDI value will be lower than the mean time to repair: 2.6787 h/occ.

In the case with 8 block agents (C4), we notice the best system reliability indices. For this case, the restoration process is always faster than 1 minute and the outages are considered only in the faulted portion of the system. Comparing the results of C3 and C4, we notice an improvement of 33% in SAIFI indices, however, as the restoration process is also fast in C3, the values of duration indices are similar to each other. As only customers connected in faulted branches stay without supply during repair time, the CAIDI indices will be the same of the base case. Due to its features, it is possible to verify that an increased number of blocks would not provide additional improvement in the reliability indices. If the decentralization is increased to extreme levels, reliability indices might be depreciated due to the increase in the total agent communication time to achieve the restoration processes.

VI. CONCLUSION

The proposed solution based on agents and blocks is a flexible hybrid approach (centralized and decentralized) to the restoration problem. The centralization is provided by a single block agent responsible for all system reclosers/switches and the reconfiguration within the block. The decentralization (of control) is provided by several independent block agents that are not directly aware of other agent's demands and constraints. The global reconfiguration is achieved by block agents cooperating by means of the CNP applied in the scope of a neighborhood. The proposed approach does not substitute all actions deliberated at control centers in all operating scenarios, but provides an interesting solution to decentralize some restoration procedures.

Results with the IEEE 123 node system show that the proposed approach can be used to improve reliability indices. Considering communication latency, it can be noticed that a centralized MAS approach can take more time until the system is completely restored and more customers can experience sustained interruptions. Dividing the system into 3 and 8 blocks, we see that the expected reliability indices are close to each other. Additional decentralization is not envisioned to provided improved reliability indices.

In future works, different communication protocols will be implemented using the concept of co-simulation in order to verify the best trade-off between cost and latency for the restoration process. Furthermore, the impact of allowing meshed/ring operation within the restoration process on the distribution reliability indicators is envisioned to be investigated.

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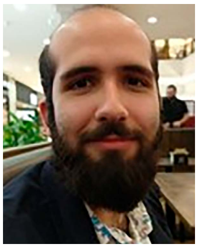

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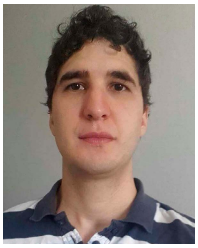

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