New Solutions for Fault Detections and Dynamic Recoveries of Flexible Power Smart Grids

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Abstract: This research paper deals with fault detections and dynamic recoveries of electrical smart grids that should be flexible and automatically adapted at run-time when faults occur on lines or devices. These grids are composed of three levels of power lines: High Voltage Lines ($44KV$), Medium Voltage Lines ($11KV$), and Low Voltage Lines ($380V$). In order to control the complexity of detection and deduction, we propose new relations between faults. We define also a multi-agent architecture to allow dynamic recoveries where two types of agents are defined: static agents and mobile agents. Static agents have as a task the detection of local faults on power lines and the recovery of their normal behaviors by using a local knowledge-base. The mobile agents are created to dynamically move on lines and to find new solutions when no local solution is found. To validate and test our approach, we present experimental results showing the originality of the paper's contribution by assuming a case study.

1 INTRODUCTION

Faults and blackouts may be caused by the worsen system conditions such that short-circuit, overloaded loss of power plants, protection hidden failure... (Lu et al., 2006). Around the world, there are many definitions of smart grids including big amounts of multidimensional characteristics. Smart grids can be seen as the modernization of the current electric grid through the intensive use of communication technologies, the integration of renewable and green energies to decarbonize power systems, as well as the improvement of both security and reliability of the network and, even, the addition of new smart electric hardware devices (like meters, storage devices, sensors...). The importance of the damages caused by power breaks and outages, as well as, the classical centralized production architecture have encouraged and inspired researchers to work on it in order to bring changes on power grids and, even, on their infrastructures. The majority of the related works deployed Multi-Agent Systems (MAS) in the domain of power networks to ensure a communication between several components of the network and to organize their tasks. (Rohbogner et al., 2012) discusses what is an agent in the context of smart grids and (Endriss et al., 2004) discusses the problem of checking an agent's conformance to protocol.

In this paper, we address new problems related to the performance of Smart Grids such as the deduction of faults as soon as possible and the optimal recovery with feasible run-time solutions. We propose, a novel agent-based approach for the fault detection and recovery in the context of electrical smart grids when faults occur on lines or devices. To control the complexity of detection and fault deduction, we propose new relations between faults to define our new efficient fault resolution method. This new fault categorization allows the forecast of other consequent faults by deduction. We define also a multi-agent architecture to allow dynamic recoveries composed of three types of agents. To reduce the time required for the system recovery, our solution ensures the update at run-time of data base agent when new solutions are found. These solutions may be, directly, used when the same fault occurs again. The originality of our work lies, also, in the agent mobility allowing; (i) a speed and useful information exchange, (ii) a decentralized new solution as mobile agents can move over the grid and (iii) the best solution at any time as the calculus is done at real-time. In Section 2, we

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present the state of the art. In Section 3, we formalize and characterize smart grids, fault detection and deduction and propose new relations between faults. In Section 5, we expose the deployed multi-agent system to be composed of static and mobile entities in order to search, respectively, local and distributed solutions. Section (6) presents our system recovery approach. And in Section 7, we test our solution for several scenarios in a simulated case study.

2 STATE OF THE ART

Over the last years, many researchers worked on different topics and concepts relative to power networks and smart grids. There is an important number of works relative to the problems of fault detection in power systems, self-healing and system recovery... The majority of the proposed approaches in the literature use MAS. A MAS is a decentralized system to be composed of a set of agents placed in some environment of software agents (McArthur et al., 2007b). (Rohbogner et al., 2012) shows that distributed hierarchical control structures are more efficient than central ones. A new useful concept appears which consists of dividing the network on subnetworks, called micro-grids or ”islands”, is highlighted. Distributed infrastructures decentralizing the control imply, generally, the deployment of Distributed Energy Resources (DER). Based on this concept, (Chen et al., 2010) showed that it is possible to reduce the likelihood of dramatically cascading failures, even, when integrating a small number of local generators into the power grid. In fact, thanks to this strategy based on DER and decentralized power system control, (Rahman et al., 2007) proposed a concept of micro-grids working during normal operation and, also, in case of failures, as islands independent of the main grid and supplied by local generators. (McArthur et al., 2007a) and (McArthur et al., 2007b) investigates and studies the higher value-added by (MAS) to power industry. (Tate and Overbye, 2008) uses the Phasor Measurement Unit to detect simple line outages and (Tate and Overbye, 2009) uses it to detect double line outages and to identify network parameter errors. Other works on failure identification and diagnosis include (Cai et al., 2010), (Calderaro et al., 2011), (He and Zhang, 2010) and (Russell and Benner, 2010). (Vyatkin et al., 2010c) proposes a distributed MAS composed of a number slave agents called BAGg and only one unique master agent called FAG - centralizing the control in the power grid system and achieving a self-healing action through fault location and power restoration. This MAS architecture was proposed in (Nagata and Sasaki, 2002) and was used, also, in (Zhabelova and Vyatkin, 2012) integrating Intelligent Logic Nodes for self-healing power system in case of circuit ruptures. These two industrial standards were combined, in (Vyatkin et al., 2010b), to develop an intelligent control architecture for smart grids.

After these short observations on related works, we draw the following conclusions. As we previously mentioned, there are many research works focussed on fault detection and self-healing in power systems. Some of them detect and repair only one type of encountered fault(s) but, neither of them studies the consequent faults. For example, (Vyatkin et al., 2010a) handles the case of only one fault type occurs (electricity break due to a tree falling on an electric line). In our paper, we are looking for formalizing the strategy of fault detection and resolution. A step of fault analysis and categorization is necessary to guide the resolution strategy. In the other hand, we note that the majority of the proposed solutions are based on MAS deploying many agents making the communication process very expensive. *Rahman and al.* proposes, in (Rahman et al., 2007), an efficient approach of power systems self-healing based on specialized micro-grids but it is very expensive in terms of communication costs (as they deploy 7 agents). They reduced the number of agents to 4, in (Pipattanasomporn et al., 2009), in order to decrease the response time but the used fact bases are inextensible. (Vyatkin et al., 2010c) deploys only a unique one master agent FAG and multiple BAGs leading to a centralized control power system and to a big number of BAGs. Whence, it is important to minimize the number of agents in order to reduce the required communication costs. In our approach, we propose a small number of agents to be deployed and to instantiate mobile agents in order to reduce the required response time in order to find a solution.

3 SMART GRID CHARACTERIZATION

Generally, electric grids involve three voltage levels: High Voltage Line (HVL), Medium Voltage Line (MVL) and Low Voltage Line (LVL). Commonly, we have principal lines which are operational and emergency lines used when the first ones are in failure. In our study, the electric grids are formed by three principal electric components interconnected through electric lines. These components are: **(i) Power Generators** (PG) that produce high voltage energy transported through HVL. **(ii) Down Power Transformers** (DPT) that transform the received electricity from a voltage level to the lower one. We consider two types of power transformers: The Medium Voltage Transformer (MVT) and the Low Voltage Transformer (LVT). **(iii) Consumers** (as end-users in electrical grids): we distinguish Medium Consumers (MC) which are supplied by MVT through MVL and Low Consumers(LC) which are supplied by LVT through LVL.

In our system each component and electric line C is characterized by:
1 - its activation state, $A(C)$, as in(1):

$$A(C) = \begin{cases} 0, & if\ C\ is\ deactivated \\ 1, & if\ C\ is\ activated \end{cases} \tag{1}$$

2 - its voltage level, $VoltLevel(C)$, as in (2):

$$VoltLevel(C) = \begin{cases} 1, & if\ C \in high\ voltage\ level \\ 2, & if\ C \in medium\ voltage\ level \\ 3, & if\ C \in low\ voltage\ level \end{cases} \tag{2}$$

Each High Voltage Line L is defined by its transported load, $TranspL(L)$. While, the Medium and Low Voltage Lines L_i are defined by their distributed load $DistL(L_i)$.
The Power generators are characterized by the produced power $ProdPow$. While each power transformer X is characterized by its transformed power $TransfPow(X)$ and its priority. The priority of a transformer X, $pr(X)$, is calculated by equation (3):

$$pr(X) = \sum_{i=1}^{n}(pr(S_i)) / \sum_{j=1}^{m} pr(P_j) \tag{3}$$

where S_i is a supplied device, P_j is a power grid device, n is the number of supplied devices by X and m is the the number of all power grid's devices.
Each consumer X is characterized by its:
1 - rank, $rank(X)$, which is its relative place in the supplying line,
2 - priority, $pr(X)$, which represents the priority of the consumer X.
3 - required load, $ReqLoad(X)$, which represents the load to need,
4 - received load, $ReceivLoad(X)$, which is calculated by summing the loads distributed by the n incoming lines L as mentioned in (4).

$$ReceivL(X) = \sum_{i=1}^{n}(DistL(L))) \tag{4}$$

4 SYSTEM CHARACTERIZATION AND FAULT CATEGORIZATION

The robustness of electrical grids is proven through their ability of managing and facing all eventual sub-merging problems. In this section, we propose a set of minimum conditions characterizing the system.

4.1 System Operating Conditions

To insure the healthy operation of the electric grid, the following conditions have to be verified.
1 - Activation Constraint: The activation states of all involved electric components have to be conserved. For a High Voltage Grid, this condition is defined by:

$$(A(PG) = 1) \wedge (A(HVL) = 1) \wedge (A(MVT) = 1) \tag{5}$$

2 - Stability Constraint: The stability of the power grid must be maintained by keeping the frequency of all electric components and the voltage of all electric lines, approximatively, equal to the respective prefixed default values f_0 and U_0. For a High Voltage Level, the stability constraint is defined by:

$$\begin{gathered}(freq(PG) \approx f_0) \wedge (volt(HVL) \approx U_0) \\ \wedge (freq(MVT) \approx f_0)\end{gathered} \tag{6}$$

3 - Flowing Load Constraint: The safe and secure operation of power systems depends, also, on loads flowing into the grid. In fact, they must respect the capacities of the deployed components. These loads must, also, respect the constraint relative to both required and received loads by a consumer X as in (7).

$$ReqL(X) \leq ReceivL(X) \tag{7}$$

To avoid the under-voltage and over-voltage problems, each consumer X should be, sufficiently, supplied. Therefore, the received loads should not be less than their minimum capacities and should not exceed the devices capacities. The violation of one of these constraints leads to faults.

4.2 Fault Classification

The encountered faults can, easily, propagate through electric lines from the sub-grid on which it occurs to another one as the power system is a mesh network to be composed of inter-connected electric components. We define faults as consequences of one or some unsatisfied constraints. Based on the constraints presented in Section 4.1, the faults that can occur on power grids may be; switching-off (deactivation), instability, under-voltage, over voltage and isolated sub-grids. The open-circuits present a consequent fault to the violation of constraint 1 or 2 or both of them. The consequences of this fault are summarized by Table 1. As the dissatisfaction of only one constraint can engender multiple faults, we look for minimizing the

Table 1: Isolated sub-grids constraints.

Fault origin	Isolated Sub Grid	Consequences
$freq(PG) \neq f_0$	$A(PG) = 0 \wedge A(MVT) = 1 \wedge A(HVL) = 1$	$ProdPow(PG) = 0 \wedge TranspL(HVL) = 0$ $\wedge TransfPow(MVT) = 0$
$freq(MVT) \neq f_0$	$A(PG) = 1 \wedge A(MVT) = 0 \wedge A(HVL) = 1$	$TransfPow(MVT) = 0$
$volt(HVL) \neq U_0$	$A(PG) = 1 \wedge A(MVT) = 1 \wedge A(HVL) = 0$	$TranspL(HVL) = 0 \wedge TransfPow(MVT)$ $= 0$

faults to be resolved and guiding the search for solutions. For that, we propose new definitions for dominant and equivalent faults based on new relations. We denote the fault set by F and the i^{th} fault by F_i such that: $F_i \in F / i \in N$.

Definition1: Dominant Fault. Let F_i and F' be, respectively, a fault and a subset of faults such that $F' \subseteq F$. Let us consider a component X connected to a set of components Y such that $|F'| = |Y|$. A fault F_i on a component X is said to be dominant of a fault F_j on a component Y_j and noted by: $F_i(X) \rightarrow F_j(Y_j)$ if for each $F_j \in F'$, $Y_j \in Y$ and $j = 1, ..., |F'|$:

$$\begin{cases} VoltLevel(X) < VoltLevel(Y_j) \\ \quad or \\ VoltLevel(X) = VoltLevel(Y_j) \; and \\ rank(X) < rank(Y_j) \end{cases} \tag{8}$$

The resolution of either the dominant or the dominated fault(s) resolves the problem. This strategy allows to reduce the required time of resolution.

Definition2: Equivalent Fault. Let F_i and F_j be two faults. Let us consider two connected components X and Y. The faults F_i and F_j, respectively, on the components X and Y are said to be equivalent and noted by: $F_i(X) \Leftrightarrow F_j(Y)$ if

$$VoltLevel(X) = VoltLevel(Y) \; and \; rank(X) = rank(Y) \tag{9}$$

In fact, the resolution of only one of the equivalent faults can resolve the problem. These new relations allow us to control and reduce the complexity of faults by deduction. The advantage is, particularly, observed in the case of multiple equivalent faults, as we are focused on resolving only one of them.

5 NEW ARCHITECTURE FOR FLEXIBLE SMART GRIDS

The resolution of the occurred faults can be done, either, locally by taking a simple and systematic reaction or by searching new solutions among the other sub-grids. We propose, then, the use of multi-agent paradigm to implement our distributed system decentralizing the control. It ensures the fault detection and deduction as well as the real time resolution to provide the best solution. Our MAS is composed of three types of software agents:

- Reconfiguration Agent: Each RAgent is responsible of the continuous supervision and maintaining of the healthy operation of the power sub grid under its scope. It is composed of a set of rules describing its behavior.

- Mobile Agent: A MAgent is a software entity moving, through electric lines, among the connected components of the smart grid to collect some information.

- Data Base Agent: The DBAgent is responsible of the management of the data base relative to the power system. It contains, mainly, the new solutions found by our MAS system as well as all the information relative to the whole power grid structure as well as the history of all the encountered faults and the corresponding solutions. It may be requested by both RAgent and MAgent about information relative to the power system. It should update its data base for each new solution found by MAgent. The DBAgent may be requested to avoid searching solutions for problems already resolved.

In order to reduce the communication cost, we associate one RAgent to each electrical sub-grid. Hence, we assign one RAgent to each PG, MVT and LVT. The RAgents have, then, to supervise the concerned component as well as the components directly supplied belonging to the voltage level below. We deploy only one central DBAgent (Figure 1). In fact, the number of DBAgents depends of the whole considered grid size and, also, of the cardinality of sub-grids formed from the global grid, as well as, of the size of knowledge to be stored.

6 SYSTEM RECOVERY

In the current section, we present how our MAS operates according to the power system circumstances.

6.1 Fault Detection and Local Solutions

The RAgent sensors must, continuously, observe their environment in order to detect all changes and anoma-

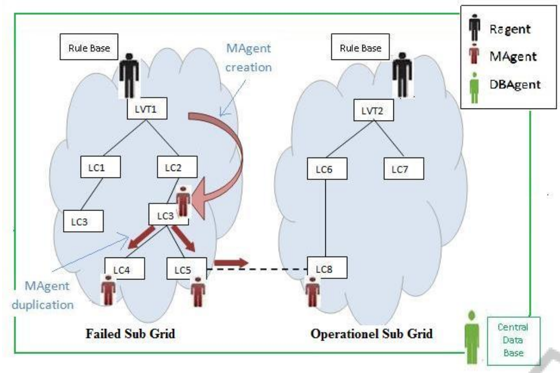

Figure 1: Example of agent assignment: attributing one RAgent to each sub-grid, MAgent are created by RAgent which can be cloned in bifurcation and unique DBAgent to the overall power grid.

lies (unsatisfied constraint) on any electric component. When a fault is detected on the component X, the concerned RAgent begins by isolating the component or line responsible of this anomaly (X) such it is presented by Algorithm 1. Then, the RAgent in question categorizes the occurred fault as it is described by Algorithm 2 in order to guide the search for local solutions where F is the fault detected on X. A local solution consists of finding a deactivated emergency line belonging to the supervised sub-grid SG and supplying, sufficiently, X as it is described in Algorithm 3. When there is more than one local solution, the RAgent chooses the one having the bigger remaining load according to the (10).

$$Maximize(\ DistL(eL) - ReqL(X)\ ) \qquad (10)$$

Algorithm 1: Fault Detection and Isolation.

Require: SensorDetection $\neq \oslash$
if $\exists$ FrequencyProblem(X) **then** Isolate(X)
if $\exists$ VoltageProblem(L) **then** Isolate(L)
if $\exists$ Isolated(X) **then** Categorize the occurred faults
if no LocalSolution **then**
Request DBAgent(Problem)
if $\exists$ Solution in DB **then** call Effectors
else create MAgent
if $\exists$ Under-voltageProblem OR $\exists$ Over-voltageProblem **then** create MAgent

When no local solution is found, the RAgent requests the DBAgent about a solution already found for the encountered problem. If no solution for the occurred fault is stored in the data base, the RAgent searches for a cooperative solution from the neighbor sub-grids. For that, the RAgent creates an MAgents to obtain information about the components belonging to the connected sub-grids. Based on the received information, the RAgent creator decides about continuing or not with the studied alternative -ie. validate or not this solution or sub-solution.

Algorithm 2: Fault Categorization.

Require: F: the detected fault
if F is dominant fault **then**
call(RAgent Local Solution) on the component corresponding to the dominant fault
if no found solution for the dominated fault **then**
call(RAgent Local Solution) on the components corresponding to the dominated faults
end if
end if
if F is an equivalent fault **then**
call(RAgent Local Solution) on the components corresponding to the equivalent faults
end if

Algorithm 3: RAgent Local Solution.

if $\exists$ deactivated emergency line incoming to X **then**
choose the one having the bigger positive remaining load
call effectors to execute solution
else if no local solution **then**
Create MAgent on X
end if

6.2 Distributed Search For Solution

Algorithm 4 presents how a MAgent MA_i is created by a RAgent RA_j on a failed component C to move dynamically on lines and visit all the devices connected to C through the existing outgoing lines called paths. At each visited device, MA_i notifies RA_j by sending a message. This message contains some information that are; 1- the remaining load (ReceivL - ReqL), 2- the cumulative priority by adding the priority of the visited component and 3- information about the end of the taken path (if there is no connected component to be visited ie- no outgoing lines then MA_i reaches the end of the taken path). This message allows RA_j to validate or not the sub-solution/solution provided by each MA_i and even to choose the best one using the utility evaluation expressed in (11). A valid sub-solution should not have a negative or a null remaining load when the end of the visited path is no yet reached. A valid solution should not have a negative value for the calculated remaining load when the end of the visited path is reached. When the visited component has more than one outgoing line (connected to more than one components), MA_i will be duplicated in order to analyze all the existing alternatives or paths. The duplicated agents are called clones. Each clone takes only one line at a time and all the clones operate simultaneously to decrease the required time (Algorithm 5). Each component should be visited at most once by the same MAgent to ensure that the resolution terminates.

$$Maximize(\sum(ReceivL(X) - ReqL(X)) + \sum pr(X)) \quad (11)$$

Algorithm 4: RAgent New Solutions.

InstantiateMAgentOn(X)
for each MAgent created **do**
  switch (received message(RL, cpr, stateEOP))
  case sub-solution**:**
    Check validity of the sub-solution
    if invalid sub-solution **then**
      destroy MAgent
    end if
  case solution**:**
    Check validity of the solution
    if valid solution **then**
      store the solution
    end if
    destroy MAgent
  end switch
end for
if no stored solution **then**
  send a reconfiguration request to user
else
  choose the best solution according to (11)
  call effectors to execute solution
  request DBAgent for adding new solution
end if

7 EXPERIMENTATION: CASE STUDY

In this section, we present an example of an electric grid to be composed of 2 PG, 10 DPT (4 MVT and 6 LVT) and 24 consumers (7 MC and 17 LC). It contains 45 lines (4 HVL, 18 MVL including 5 $eMVL$ and 23 LVL including 6 $eLVL$). We are interested on failure as well as their causes in order to find good and satisfactory solutions. We study two type of fault cases to validate and test our approach that we developed in Java platform. We used the Aglet API to develop the Mobile Agents. The simulations were done over an electrical network which is simulated by reference Matlab of Simulink.

Algorithm 5: MAgent Movement.

for each visited component Y **do**
  calculate RL(Y)
  calculate cpr$Y$
  if no outgoing lines from Y **then**
    $stateEOP = true$
  else
    $stateEOP = false$
  end if
  send message(RL(Y), cpr(Y), stateEOP(Y))
  switch (number of outgoing lines from Y)
  case =1**:**
    call (MAgent Movement on the unique connected component to Y)
  case > 1**:**
    cloning MAgent
    for each clone or for each connected component to Y **do**
      call (MAgent Movement on the component to be visited)
    end for
  end switch
end for

7.1 Local Fault Recovery

Let us consider the case where there is a problem on the line $LVL2$ and let us suppose that the voltage value detected on $LVL2$ is equal to $80V \neq U_0$ (Figure 2). This value involves an instability problem on the concerned sub-grid. This voltage instability is detected and identified by $RA1$, the RAgent assigned to the sub-grid supplied by $LVT6$. $RA1$ reacts, then, and isolate the fault by deactivating $LVL2$ (Figure 3). As a consequence to this deactivation, there

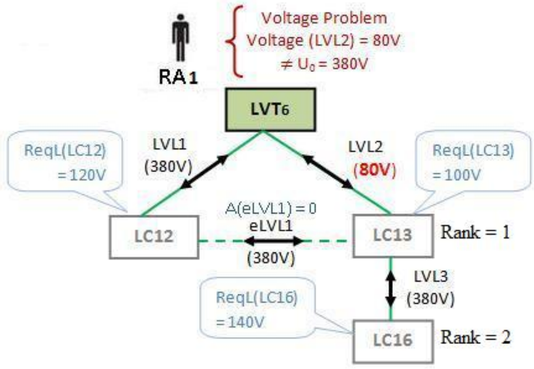

Figure 2: Detection of a voltage problem on $LVL2$.

is an emergence of faults $F1$ and $F2$ which are detected, respectively, on $LC13$ and $LC16$. As defined in section 4, $F1$ is dominant on $F2$. Hence, $RA1$ tries to resolve the dominant fault $F1$. For that, a local solution is searched and $RA1$ looks for the existence of emergency lines in the supervised sub-grid. Since, there is an emergency line ($eLVL1$) incoming to $LC13$ and $eLVL1$ is able to, sufficiently, supply $LC13$. $RA1$ executes this feasible solution and activates the emergency line $eLVL1$, which resolves the problem. The detection and resolution CPUs, were, respectively, equal to $1,78s$ and $0,69s$.

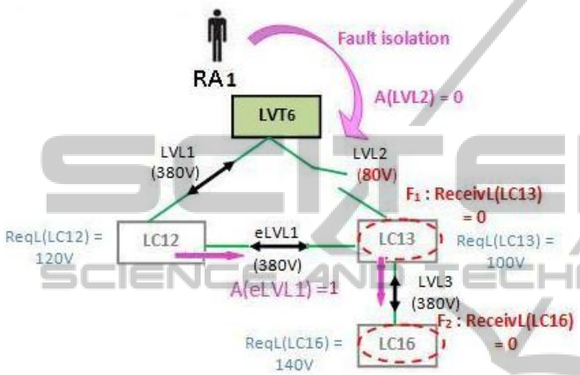

Figure 3: Problem Localization and Resolution.

7.2 Distributed Fault Recovery

The second studied case is about a frequency problem observed on the transformer $LVT5$ (Figure 4). Let us suppose that the frequency value detected on $LVT5$, at $11PM$, is equal to $25hz \neq f_0$. The low voltage consumers $LC2$, $LC3$ and $LC6$ represent, respectively, a hospital, a university and a policy office having the respective priorities 1, 3 and 2. At this time, $LC3$ does not require electricity while $LC2$ and $LC6$ require each one $180V$. This instability of frequency is detected by $RA2$, the agent assigned to the sub-grid supplied by $LVT5$. Then, $RA2$ isolates the fault by deactivating $LVL1$. As a consequence, 3 faults; F_1, F_2 and F_3 occur, respectively, on $LVT5$, $LC11$ and $LC17$. F_2 and F_3 are faults dominated by F_1 as illustrated by Figure **??**. As it is not possible to resolve F_1 since $LVT5$ requires a physical repairing, $RA2$ looks for resolving the dominated faults F_2 and F_3. There is no local solutions as there is no emergency lines belonging to the sub grid. Then, $RA2$ requests the DBAgent for searching a solution, stored in its central data base, to the encountered problem. As this problem happens for the first time over this sub grid, the DBAgent does not return any solution. Thus, $RA2$ instantiates a MAgent $MA1$ on $LC11$ to search new solutions from other

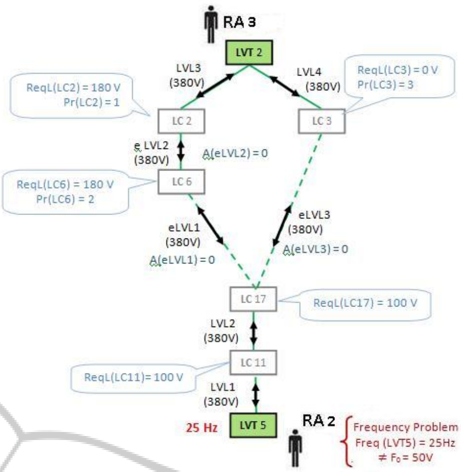

Figure 4: Detection of a frequency problem on $LVT5$.

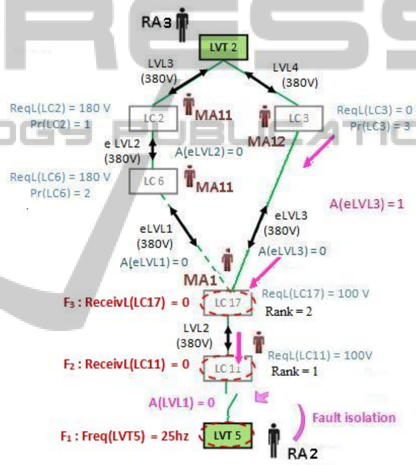

Figure 5: Problem Localization and Resolution

sub grids connected to the supervised one. After visiting $LC17$, $MA1$ is duplicated; the first clone $MA11$ visits $LC6$ and the second one $MA12$ visits $LC3$. Both of them execute Algorithm 5 at each visited component. The RAgent creator analyzes the results sent by these two clones $MA11$ and $MA12$. For $MA11$, the calculated remaining load is equal to 0 knowing that it has not yet reached the end of its path (as $LC6$ has an outgoing line). $MA12$, visiting $LC3$, reaches the end of its path (as $LC3$ has 0 outgoing line) with remaining load equal to $180V$. At the next iteration, $MA11$ reaches the end of its path with a negative remaining load equal to $-180V$ which is invalid as it is negative. The two responses are found on, respectively, $1,17s$ and $1,09s$. $RA2$ chooses the second solution provided by $MA12$ as the first one is rejected; it consists of activating $eLVL2$. There were only five messages exchanged between our deployed agents $RA2$ and $MA1$.

8 CONCLUSIONS

In this paper, we propose an agent-based approach to resolve the faults in power systems which run according to the following rules; (i) detect and localize the problem,(ii) identify the problem by checking constraints, (iii) categorize the occurred faults and (iv) choose the suitable strategy of search for solution (local through RAgent or distributed through MAgent) to accelerate the resolution. In future works, we are interested in reducing the number of the deployed agents by integrating a knowledge base in RAgents to store local solutions in order to reduce the requesting time. We are, also, interested in investigating multiple and even concurrent faults at the same time. The use of smart storage devices present, also, an interesting issue for us as well as the failure rates to forecast failures.

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