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A Mathematical Model for Restoration Problem in Smart Grids Incorporating Load Shedding Concept

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ABSTRACT

The automatic restoration process is an important part of advanced distribution automation which seeks to automatically restore outage loads in smart grids. This ability of the smart grids improves the reliability and reduces the service interruption period. According to the importance of the restoration problem, this work focuses on modeling this problem in a simpler manner which is appropriate for smart grid. Since the smart grid agents can perform distributed computational activities and make decisions individually, the proposed model is constructed as a routing problem in a virtual graph which is developed based on the out-of-service areas in the main grid. This model is solved instead of the commonly used NP-hard restoration problem during decision making process to obtain the optimal restoration plan. The presented routing problem which is constrained by some power system operating constraints considers the load shedding concepts and gives the shedding program with respect to the load prioritizations. It can be solved by a linear binary programming technique such as branch and bound. Finally to demonstrate the designed restoration algorithm capabilities, a standard test system is selected and the method is implemented on it. The given results show the applicability of the proposed model.
KEYWORDS: Linear binary programming; Load shedding; Restoration problem; Smart grid

INTRODUCTION

In smart grids, service restoration is an important appearance of advanced distribution automation which transfers unfualted and outage loads to other substation and supplies as many customers as possible in the shortest time automatically. The automated actions during restoration process reduce the interruption costs and improve the quality of service using the existing microprocessor based and automated switchgear at nodes. These switches can be divided into two types: normally closed sectionalized switches and normally opened tie switches. The status of these switches must be regulated properly such that the radial topology of distribution system is maintained. During emergency operation, the switches can be changed autonomously such that power can be served from different feeders to the outage area. This ability is an important change of paradigm in distribution networks operation achieved by smart grids deployments. According to [1], real-time information which is available by bidirectional communications and automated controls, the out-of-service areas can be automatically restored and the service interruptions are mitigated.

According to the importance of the restoration problem, in recent decades, many researches were focused on this issue and different approaches have been proposed to obtain the best switching operation plan to reenergize the out-of-service areas in presence of the operating limitations. Mathematically, the restoration problem is a combinatorial non-linear multi objective optimization problem with some linear and non-linear constraints. The constraints of this problem are related to the power system physical and operational constrains such as source, line/cable loading, nodal voltage and often radial network constraints. The proposed reconfiguration approaches can be categorized as deterministic mathematical programming method [2-6], heuristic techniques [7-9] and knowledge-based systems [10]. There are several common characteristics of these approaches. First, all necessary information is collected from fields at a centralized computer system. Second, large amount of data transferring and low-latency communication are imposed on the system. Third, the control center requires expensive computing capability. These mentioned characteristics comprise barriers that aggravate even more in the case of medium voltage (MV), mainly due to their extent and substantial branching and also large number of nodes that have to be monitored. As a result, centralized techniques have some difficulties to be implemented in smart grid with real-time sensor measurements and various intelligent electronic devices.

Meanwhile, multi agent system (MAS) as a distributed problem solving approach utilizes a distributed control at the component level and uses peer-to-peer communication for collaborating agents achieve near global objectives and overcome disadvantages of centralized techniques. According to the distributed intelligence in smart grid and existing online measurement, MAS seems an appropriate solving method for restoration problem. Recently, some research has been performed to develop MASs in service restoration [11-19]. In [11], MAS architecture has been utilized for only the service restoration without considering the load

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shedding and priorities. In [12, 13], MAS framework has been developed for the service restoration problem, incorporating the load shedding concept. Load variation and prioritization have not been considered in these mentioned two studies. In [14, 15], the restoration problem has been investigated in the MAS architectures, considering load prioritization and shedding concepts. A completely distributed algorithm has been proposed in [16] for the self-healing mechanism in distribution systems with distributed energy resources (DES). In [17, 18], an agent based control framework has been presented for controlling the self-healing process considering the peak load in duration of the fault repair. A MAS architecture including agents with local views has been proposed in [19] to realize the automatic restoration mechanism. There are two common characteristics of the mentioned MAS approaches have been proposed in the past [11-19]. First, the decision making policies in available studies are based on the learning methods or expert-based systems which often achieve near global objectives. They don't investigate the optimality of their obtained distributed solving approaches. Second, they require huge databases to restore statistical data for their expert-based decision makers. They don't consider the advantages of the mathematical programming methods to eliminate this requirement. To overcome this barriers a distributed restoration problem approach is proposed in this paper to guarantee the optimality of the obtained restoration plan and reduce the amount of necessary information for distribution system restoration.

This paper will explore the agent based restoration problem and aims to find an optimal restoration plan. In the proposed MAS architecture, two categories of agents, including zone and feeder agents, negotiate together and exchange local information. Furthermore, they make decision using the received information through a hybrid decision making policy. This policy is designed based on the expert-based system and mathematical programming techniques to be gained from the advantages of both methods simultaneously. At the same time, the restoration problem is modeled simply and a novel approach is developed for obtaining an optimal restoration plan incorporating the load prioritization and shedding. The presented model is a linear binary programming problem which its dimension is lower than the main mixed integer NP-hard mathematical problem commonly used for modeling the restoration problem. In other words, this paper focuses on introducing a mathematical model for restoration problem such that the complexity of the proposed method and its data accuracy dependence is lower than the commonly mixed integer programming method used for solving restoration problem. In this model important practical issues related to the restoration problem including load prioritization and shedding is considered. The suitability and capability of the developed method is demonstrated by implementing it on IEEE standard test system. The given results illustrate the applicability of the presented algorithm with accurate restoration plan and load shedding program.

The rest of this paper is organized in six sections as follows. Section 2 introduces a multi-agent framework for the self-healing mechanism in the distribution systems. Section 3 presents the decision making policy and advanced mathematical restoration model. Section 4 illustrates the evaluation of the multi-agent control framework by means of the IEEE 33-node test distribution systems. Finally, the paper conclusions are drawn in Section 5. A list of all the symbols used in the paper is included after the conclusions.

Agent Based Control Architecture

In smart grids, the agents are equipped with the intelligent ability to communicate and negotiate together to determine the current states of the system and make decision to set the status of their actuators to reenergize the out-of-service areas in a shortest period. Therefore, in this section, a MAS control structure is proposed for automated service restoration in smart distribution system. In the proposed structure, each distribution feeder is divided into some segments, namely zones, with the location of the switching devices which are placed on the boundary of each segment. In the presented MAS, a control agent is assigned to each zone as a zone agent to communicate, make decision and calculation. Moreover, a feeder agent is assigned to each feeder to determine the operating situation of each feeder and communicate with other adjacent feeder agents. Agents communicate together to coordinate their performance based on the agent communication language (ACL) [20] which is developed in 1996 by foundation for intelligent physical agents (FIPA) [21]. Each zone agent monitors the nodal voltage and branch currents at its corresponding zone and calculates two important factors which can demonstrate the operating situation of that zone. These two factors can be considered as minimum nodal voltage at a zone and minimum spar current capacity of lines at a zone. Zone agents send these monitored data to their feeder agent through sending messages if the relative feeder agent seeks to calculate its available capacity to reenergize additional loads. Furthermore, feeder agent communicates with other feeder agents which are connected with them by a tie (normally opened) switch. During the restoration process, an outage zone can be transferred to a backup feeder to be reenergized if that feeder has enough available capacity to satisfy the required power consumption of loads at that outage zone.

One of the important concepts of restoration problem is the load prioritization. Considering the lack of power supply during the emergency condition the restoration process should be started from reenergizing the highest priority loads and then other loads are allowed to be restored. If any backup feeder has sufficient capacity to restore the out-of service areas, the restoration process is conducted as a group restoration. Otherwise, the outage areas are divided into some parts such that each part is restored via an individual feeder.

In this work, the load pattern and prioritizations are assumed to be available initially for each zone agent. To guarantee the satisfaction of power system operating constraint during the restoration process the peak load over the restoration period is used from the load pattern to find the restoration plan.

Coordination between Agents

The agents coordinate together in the proposed MAS using the monitored and initiated data to find the best restoration plan. After isolating the fault area, the downstream zones are disconnected from the grid and enter the outage situation. The feeder agent monitors this operating situation and starts to negotiate with other neighboring feeder agents which are connected to them via tie switch as backup feeder agents. The backup feeder agents communicate with zone agents placed on the relative feeder and ask them about the available capacity. A backup feeder agent with a maximum capacity is selected as a leader of decision makers to make some decisions and find the switching plan. The obtained restoration plan is given to other agents via sending message.

In the proposed MAS, the agents coordinate their performance using a hybrid policy consisting of expert-based system and mathematical programming method. On one hand, the policy is designed with respect to the important aspects related to the operational practices of the restoration problem. In other words, some expert-based rules are extracted using these aspects to coordinate the agent performance. On the other hand, to guarantee the optimality of the performance of the agents during the restoration plan, the decision making process is taken into account using the mathematical programming technique. To this end a new usage of this technique is developed which is matched with the distributed nature of the proposed MAS structure. To this end, a restoration problem is simply modeled as a linear binary optimization problem which its solution denotes the optimal switching operation which should be implemented by zone agents. The developed hybrid policy is explained in the following of this section.

Expert-Based Rules

In the proposed MAS, considering some practical aspects of the restoration problem guarantees the applicability of the obtained plan. These important factors are highlighted as follows.

- In emergency condition, the available capacity of distribution feeders is limited. Therefore the highest priority loads should be restored at first. Considering this fact, a weighting coefficient, namely ω_i, is defined for i^{th} zone to identify its load priority.
- The radial topology of the distribution system should be maintained.
- If it is possible the group restoration plan is preferred, otherwise the restoration process should be done using as minimum as possible switching operation.
- Load transferring during the restoration process should be done without any voltage and line current violation. Therefore, the nodal voltage and line current limitations in each backup feeder should be considered in determining the available capacity of a feeder [17].
- An outage zone can be transfer to a backup feeder if that feeder has enough available capacity.
- If there is no enough capacity to restore the outage areas entirely, the remaining out-of-service areas should shed.

According to the mentioned points, the following expert-based rules are extracted.

Rule1. Each feeder agent calculates available capacity of the feeder with respect to the minimum available spar line current capacity related to zones placed between the substation node and the zone which connects to the damaged feeder via a tie switch. The spar current capacity of feeder j^{th}, namely $SCrC_j$ is calculated by a feeder agent as

$$SCrC_j = \min_l \left(I_l^{\max} - I_l \right), l \in L_j \qquad (1)$$

In addition, maximum allowable additional voltage drop in a feeder is an important factor in determination of that feeder capacity. Each feeder agent calculates the allowable additional voltage drop of feeder j^{th}, namely $AAVoD_j$, as its available voltage capacity as follows.

$$AAVoD_j = v_j^{\min} - 0.9^{p.u.} \qquad (2)$$

Rule2. Each zone agent monitors the sensor measurements and determines two operating factor for its corresponding zone including the voltage difference and the current difference at both sides of a zone, namely ΔV and ΔI, respectively.

Rule3. Each zone agent attaches the exchanged information of the next zones to its zone information and sends the result to the neighboring zone.

Rule4. The received information is classified as a table consisting of two columns and some rows. The first column denotes the sender zone agent and the second column includes the information such as ΔV and ΔI of a zone or minimum nodal voltage and spar line current capacity. The rows illustrate the connectivity of zones in the feeder.

Rule5.Each zone should be supplied from an entrance node to maintain the radial topology of the distribution network.
Rule6. A feeder agent can investigate the possibility of reenergizing an additional zone using (3) and (4). In other words, if (3) and (4) are satisfied the j^{th} feeder has enough capacity to reenergize the i^{th} outage zone. This rule enables feeder agent to evaluate the load flow constraints in a distributed manner.

$$\Delta V_i \leq AAVoD_j \qquad (3)$$

$$\Delta I_i \leq SCrC_j \qquad (4)$$

Rule7. Shedding the least priority loads can enable the feeder agents to restore remaining outage loads. Feeder agent gives the shedding program to relative zone agents after decision making process.

Linear Binary Programming Technique

In the presented MAS structure, the leader feeder agents with maximum loading capacity is responsible to construct a well-defined mathematical optimization model for finding optimal combinations of outage zones. To this end, it utilizes the received measurements from other zone agents including the load consumption of outage zones and available capacity of other backup feeders. The power consumption data is sent by zone agents placed in outage areas as a classified table which is explained in previous section. Moreover, the data related to the available capacity of other backup feeder is sent from feeder agents to the leader. These feeder agents receive a message from the damaged feeder and start to negotiate with zone agents to ask them about the spar current capacity and allowable additional voltage drop at the feeder. For more simplification, the leader feeder agent develops a virtual graph of the out-of-services area with the received information. This virtual graph consists of some vertices, branches and a capacity node. Outage zones which are listed in the classified table construct the nodes, while the switching devices placed between zones in outage areas builds the branches of the graph. Moreover, the capacity node is an auxiliary node which is considered as a source. This node can be connected to some zones in the graph with respect of the connection zone of tie switches in the main grid. To clarify the mentioned explanations, Fig. 2 shows a virtual graph which is developed for the out-of-service areas in the distribution system shown in Fig. 1.

As can seen, the connectivity of vertices in the virtual graph is determined based on the operating situation of the switching devices. The capacity node connects to some nodes in the graph based on the status of the tie switch in the grid. These nodes correspond to some zones in outage areas which are connected to backup feeders via tie switches.

According to the designed decision making policy, the main grid is replaced by the constructed virtual graph and the restoration problem in the main distribution system is replaced by a simple routing problem in the virtual graph. This new routing problem is a linear binary optimization problem with the objective of finding minimum number of paths in the graph for connecting as greatest vertices as possible to the capacity node without forming a loop. These paths are selected such that some constraints, which are developed with respect to the restoration problem constraints, are satisfied. Note that, the virtual graph is simpler and shorter than the main grid. Moreover, the satisfaction of some constraints (i.e. load flow constraints) is investigated in a distributed manner by agents. Hence, the complexity of the routing problem is more less that the restoration problem.

According to the solution of the optimization problem, each obtained path represents a restoration path in the grid and the vertices which are connected to the capacity node via that path denote the outage zones which are reenergized via a backup feeder. Considering the branch which the path is connected to the capacity node the backup feeder in the main grid is represented. To develop such a mathematical model for routing problem, two categories of binary variables are introduced for each zone. The first one indicates the possibility of restoring a zone by a specific backup feeder, namely x, and the second category includes a binary variable denotes the shedding of the loads at a zone, namely y. Indeed, if an outage zone is determined to be restored by a backup feeder its relative variable "x" is set as 1 and its relative variable "y" is set as 0. In the following, the proposed optimization model for restoration problem which is a routing problem in a simple graph is developed. The restoration constraints and its relative operational practices are considered.

A. The objective function

A restoration plan commonly aims to energize maximum loads using minimum switching operations. According to the routing problem points of view, this objective is equal to find minimum number of paths to connect maximum vertices of the graph to the capacity node.

$$\underset{i,\min j}{Max} \sum_i (\omega_i x_{ij} - W\omega_i y_i) \qquad (5)$$

B. Constraints

1. Nodal voltage constraints

The model considers the acceptable range in which nodal voltage can vary without violating any operating constraint. During the restoration process, load transferring should not cause to violate the voltage constraint violation at any node. In other words, loads can transfers to other backup feeder if it has enough voltage capacity. From the routing problem points, the vertices can connect to the capacity node via the j^{th} path if (6) is satisfied.

$$\sum_i \omega_i x_{ij} \Delta V_i \leq AAVoD_j \tag{6}$$

2. Loading capability of a backup feeder.
The branch current can vary without violating any operating constraints within an acceptable range. This constraint is descried mathematically from the routing problem points of view as follows.

$$\sum_i \omega_i x_{ij} \Delta I_i \leq SCrC_j \tag{7}$$

3. Radial topology of the grid
Regarding this characteristic, each outage zone should be reenergized only via one backup feeder. According to the routing problem perspective, each vertex should be connected to the capacity node via only one path. This fact is modeled mathematically as

$$\sum_j x_{ij} \leq 1 \tag{8}$$

4. Sequential nature of restoration process
In restoration process, each tie switch agent reenergizes its closest zone and then, other switching devices restore other zones sequentially. From the routing problem views the vertices can be connected to the capacity node via a path from the nearest to the furthest node. This sequence is explained mathematically, considering the topology of the virtual topology of outage area, as follows.

$$x_{ij} - x_{i-1j} \underset{i>1}{\leq} 0 \tag{9}$$

5. Restoring as many outage zones as possible
Restoration process aims to reenergize maximum possible outage zones. Hence, the possibility of reenergizing zones placed in the out-of service areas should be investigated entirely to determine the remaining outage zones which should be shed because of lack of supply.

$$\sum_j \sum_i x_{ij} \Delta I_i + \sum_i y_i \Delta I_i \geq \sum_i \Delta I_i \tag{10}$$

6. An outage zone is restored or shed

$$y_i + \sum_j x_{ij} \leq 1 \tag{11}$$

According to (8) and (11), it can be concluded that (11) can describe the constraints 3 and 6.
The proposed model is an optimization model developed to model the restoration problem in a simple manner. The dimension of this model is a more less than the NP-hard combinatorial optimization model which is commonly used for restoration problem. The introduced model is solved by any linear binary programming method such as branch and bound [22]. Since the mathematical programming techniques give the optimal objective, this method is used as a decision making policy in the proposed MAS by the feeder agents to obtain the optimal restoration plan. Designing the virtual graph and using limited information given by intelligent sensors reduce the dimension of the problem and discover the disadvantages of centralized such techniques. In addition, expert-based rules lead to distribute some computational activities among agents and reduce the complexity of the proposed model.

Numerical Analysis

The developed control method and the proposed mathematical model for restoration problem are tested on the IEEE 33-node radial distribution system having 33 buses and 32 branches. This test system is presented in [23]. Fig. 1 shows this test system with its zones. Here, the distribution system is simulated with Matlab software as a pilot power system and the proposed decision making method is also modeled in this software. In addition, the model is simulated with Matlab using its Branch-and-Bound solver to find the optimal restoration path. A permanent three phase balanced fault which is assumed to have occurred at node7, zone4 is isolated by operating switching devices, namely SW8 and SW9.
According to the proposed algorithm feeder 1 is selected as a leader feeder agent which is received some information from outage zone agents and classifies the data as a table.

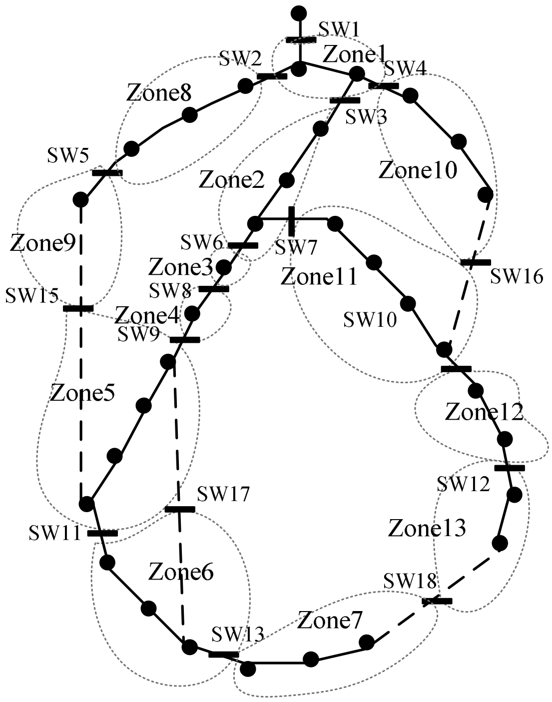

Fig 1: IEEE 33-bus test system with its zones

Moreover, it receives the capacity of other backup feeder from feeder agents. This feeder agent constructs the virtual graph, as shown in Fig 2, and develops the proposed optimization problem to find the optimal restoration plan. This optimization plan if solved by branch and bound technique and its optimal solution which denotes the connectivity situation of vertices to the capacity node via some paths. These paths are shown it Fig. 2 by dash lines. In other words, this solution illustrates the restoration paths and the outage zones which are restored with the obtained plan.

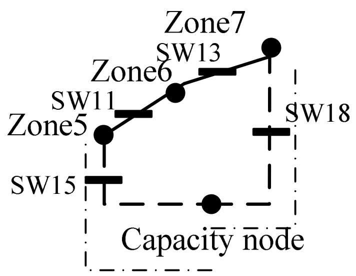

Fig 2: Virtual graph

Table I demonstrate the obtained results given from solving the routing optimization problem.

Table I: Solution of the optimization problem

Variable No.	x_{51}	x_{52}	x_{61}	x_{62}	x_{71}	x_{72}	y_5	y_6	y_7
Obtained result	1	0	0	0	0	1	0	1	0

As can be seen, the outage zones 5 is reenergized via backup feeder 1 and outage zone 7 is reenergized via backup feeder 2, while the outage zone 6 should be shed because of the lack of spar current capacity of both available backup feeders. Table II illustrates the restoration plan which is sent to relative zone agents to be implemented.

Table II: Restoration plan

Outage zone No.	Backup feeder	Restoration status
Zone 5	Feeder 1	Reenergizing
Zone 6	-	Shedding
Zone 7	Feeder 2	Reenergizing

According to the obtained results, Table III represents the switching sequence. In this table number "1" denotes the closed status and number "0" represents the opened status of a switching device.

Table III: Switching sequence

Switch No.	SW8	SW9	SW11	SW13	SW14	SW15	SW16	SW17	SW18	Other switches
Status	0	0	0	0	0	1	0	0	1	1

The obtained result demonstrates the applicability of the proposed model for restoration problem.

Conclusion

In this work, a novel model is proposed for restoration problem is smart grids. Considering bidirectional communication infrastructure and intelligent electronic switching devices, the control programs can be implemented more than previous and the restoration activities can be conducted automatically. The intelligent devices as agents negotiate together and exchange local information to make decision in a distributed manner. In such an environment, the centralized decision making techniques impose some difficulties in application on the system. Analyzing the huge amount of data in a computer center and solving restoration problem based on the common available NP-hard mathematical model is not applicable in smart grids. Hence, a simple and lower dimension model is proposed for restoration problem incorporating the smart grid features and intelligent ability of electrical devices. Unlike the commonly used restoration model, this model can be solved by linear binary programming techniques and achieve the optimal objective. Furthermore, the proposed model considers the lack of supply in the grid during the emergency condition and obtains the load shedding program based on the load prioritization. The presented restoration algorithm is tested on IEEE standard 33-bus test system and the obtained result demonstrates the applicability of the method.

Symbols

$AAVoD_j$	The allowable additional voltage drop of feeder j^{th}
I_l	The magnitude of current flows the l^{th} distribution line
I_l^{max}	The maximum allowable branch current magnitude
L_j	The set of lines placed on the j^{th} feeder
$SCrC_j$	The spar current capacity of feeder j^{th}
v_j^{min}	The lowest voltage magnitude of buses in the j^{th} backup feeder
W	It is a penalty coefficient
x_{ij}	The binary variable related to the i^{th} zone and the j^{th} backup feeder
ΔI_i	The current difference at both sides of the i^{th} zone
ΔV_i	The voltage difference at both sides of the i^{th} zone
ω_i	The priority coefficient for i^{th} zone

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