SMART DISTRIBUTION NETWORK RESTORATION USING MULTI AGENT SYSTEM

Rajan kumar Mishra
Department of Electrical Engineering
Indian Institute of Technology Madras
Chennai, India
ee12d020@ee.iitm.ac.in

K. Shanti Swarup
Department of Electrical Engineering
Indian Institute of Technology Madras
Chennai, India
swarup@ee.iitm.ac.in

***Abstract*—Distributed restoration strategy for a power system is evaluated in the present paper. This evaluates the benefit from a traditional centralized scheme in terms of speed and reliability giving economical solution to the problem. Multi agent system approach is exploited in this work to get solution faster while reducing the computational burden. Restoration problem is a multi-objective, multi-constraint problem which changes from node to node depending on their characteristics (load bus or generator bus) which can be easily incorporated in a multi agent system with individual agent requirements. This will increase the speed of restoration providing its the capability to self restore utilizing maximum capacity in given condition.**

I. INTRODUCTION

Power outages are unavoidable in large interconnected power system. Present day technology enabled us for estimating the fault. However there are some unforeseen circumstances which can not be estimated like human error, lack of information in computation, control system failures are to name a few. So it becomes vital to be prepared for these questionable eventualities. Power restoration studies allow us react quickly and reduce the time for outages. Decades of research has been undertaken in restorative action but additional effort is required to improve the restoration performance with ever increasing complexity in the network.

Restoration problem is the combinations of switching operation which is increasing with increasing the network size in terms of load and no of consumers. Several techniques have been employed in last decades to mitigate this problem. Traditionally it started with expert system [1] which is further improved with hybrid system[2] with part integration of advanced computer analysis with expert system. With advancement of computational efficiency heuristic approaches[3] came into existence. Loop control strategies[4] are deployed to increase reliability while reducing computational burdens. Later many restoration approaches,like dynamic programming[5] , automation support[6] and network reconfiguration[7], are investigated for fast recovery of the system.

Most of the system restoration algorithm conventionally are based on centralize control system are more complex day by day. Integration of distributed generation in the load end makes the traditional algorithm more computationally exhaustive. Bi-directional power flow is also needs to be considered when modernized grid with renewable sources will push power for the customer end to the grid. These advancements gave more reliable cleaner power to the grid at the cost of computational complexity. These highly non-linear multi-objective problems are increasing the computational burden on a single centralized control system which needs more time and hardware resources for an optimal solution.

At the time of restoration we are least concerned about the highly optimal solution and try to reduce the loss of load duration for the entire distribution system. Also increase in penetration of distributed generation gives us the opportunity to exploit excess power which is produced in the load end to help in the restoration process. Fortunately we have a lot of recent advancements in communication as well in information technology lately. These advancements made implementation of distributed computing along with more reliable communication between them cost effective.

Multi agent systems(MAS) are well suited to do distributed computing[8] while giving rise to sub optimal solution. As they are only concerned about meeting their own objective, they simplify the process of exhaustive computing of a traditional centralized system to small problem sets. As these have their own set of problem, the solution we get from these kind of systems are not fully optimal but sub optimal in nature. But at restorative stage of the system, time is of the essence and optimality of the solution comes next. We need a reliable communication system for MAS to work, which is easily accessible in the most remote areas of the world too. MAS have their own level of autonomy also self awareness[9] to sense its environment and act accordingly which also gives it the upper hand in a self healing algorithm. These advantages gave us the motivation to develop MAS for multi micro grid interaction for emergency restorative process.

This work is based on the power system restoration in micro-grid environment. In this work, all node in a distribution system are modeled as an agent. There are different types of agents which form the system viz. load agents, generator agents and bus agents. Each agent has their specific objective with a small set of constraints. All of them try to optimize their own objective in the smallest time possible.

978-1-4799-5141-3/14/$31.00

We also introduced the priority of the load to be fed first to the algorithm which chooses to provide power to the highest priority load initially. Rest of the generation is distributed among the load based on their own priority. Each micro-grid has their own set of load and they will serve their own load first. They will be sensing if the system is grid connected or in an islanded mode. The islanding detection method is not modeled in this work though, it is directly fed to the micro-grid with a boolean value to simplify the algorithm. Islanded micro-grid may choose based on its own setting to provide some critical load outside of its own while delaying the power of some non-essential load inside its own boundary.e.g. It might be essential to supply a nearby hospital and delaying swimming pool pump power supply. This setting is purely optional though, only few of the micro-grid are designed that way.

II. Node Constraints

The best described one liner for power system restoration procedure is given in Power and Energy Magazine[10]. It characterize the entire restoration process in three simple steps turn the light on, keep the light on and turn it back on when they go out completely or partially.

The objective of all the restorative process is to keep maximum amount of load served at any instant of time. Mathematically,

$$max \sum_{i \epsilon N} x_i L_i \tag{1}$$

where x_i is the decision variable which gives status of bus i i.e. bus i is energized or not, L_i is the load in respective bus and N is number of total bus.

There are some constraints we have to follow depending on the node characteristics.

- Load generation balance: Total load served in the system must not exceed total generation available in the system. In grid connected mode it is total power alloted to the system along with available internal generation where as in islanded mode only internal available generation can be dispatched.

$$\sum S_{Generation_i} \geq \sum_{i \epsilon N} S_{Load_i} \tag{2}$$

  Here the S represent respective apparent power for load and generation in respective buses.
- Power balance: Amount of power supplied to all the buses should be equal to sum the power provided to next down stream buses, its own load and the losses in the line. Losses can be easily computed for a radial system from voltage profile and power transferred.

$$P_i - L_i - \sum_{j \epsilon O_i} (P_j + P_{L_{ij}}) = 0 \tag{3}$$

  Where, P_i and P_j is power consumed by bus i,L_i in load connected to bus i, O_i is the number of buses fed from bus i and $P_{L_{ij}}$ is the loss in the line carrying power from bus i to bus j.

As the computation is distributed in nature, capacity constraints or the load generation balance of the system can not be computed at one point. So it is the job of each generation agent to keep track of their own capacity constraints. This is explained in detail in later section.

III. Multi agent system

Agents in multi agent system are the smallest computing entity having its own artificial intelligence in a distributed computing environment. They are modeled to have their own objective optimizing mechanism which work autonomously while interacting to its environment. Environment might be different agents in its vicinity or the data sensed from its own sensor.

Agent must have an opportunistic behavior to get to its objective while obeying all its constraints as fast as possible[11]. It should not require human interaction to reach to its conclusion i.e. it must have some level of self-governing or autonomous behavior. It should be able to sense its environment as fast as possible and should be capable to improve its state.There are different methods to describe an unit of a multi agent system i.e. agent depending on how they interact and get to the solution for their objective. Most popular MAS behavior is described by BDI architecture.

In BDI architecture an agent have three basic characteristics i.e. Belief, Desires, and interaction[12]. Belief is the facts in hand i.e. the data stored in the agent or the local information available to it. In power system point of view it is the state of the agent whether it is supplying all the load or not, how much extra power is required to energize its entire load, etc. Desire are the system constraints that should not be violated in any point of time e.g. loading limit of the connecting branch, voltage profile of the bus etc. Interaction is the negotiation capability of the agent which is the most important aspect of the agent. This is the character upon which the outcome of the system state depends.

IV. System restoration agent architecture

In this work author has considered three different type of agent depending on their working and objective. But all the agent are programmed to change their characteristics when the system demands. Basically there are three agent considered here, depending on their placement from end user to the power producer i.e. load agent, bus agent and generator agent.

- Load agent: This is the end point of the power system where the power is consumed. Its behavior can be best described by an entity who request power from its higher node till it has what it needs. It is connected to multiple node or agents. So it will request power to all of them while selecting the best possible choice depending on the amount of power they can supply and voltage profile it can get. It will sense if its complete power is supplied or not at all time if part of its load is not served it will keep on negotiating till it is met. Once the power is met it will stop negotiating and keep on sending a status requests to the power provider. It will not change its switching location till there is an additional load requirement or power denial request from its predecessor. This is to keep the switching from changing position all the time which will in turn affect the reliability indices. As the network is changing all the time we might get better solution from the present if we change the switching but it is not necessary to change the system all the time if there is no requirement change which will cause unnecessary disturbances in the system. We may introduce a reconfiguration to improve the system in a larger interval which is optional. This is the reason the solution we get is sub-optimal in nature in effect of constantly changing network condition. Interaction of load agent is given in the figure-1

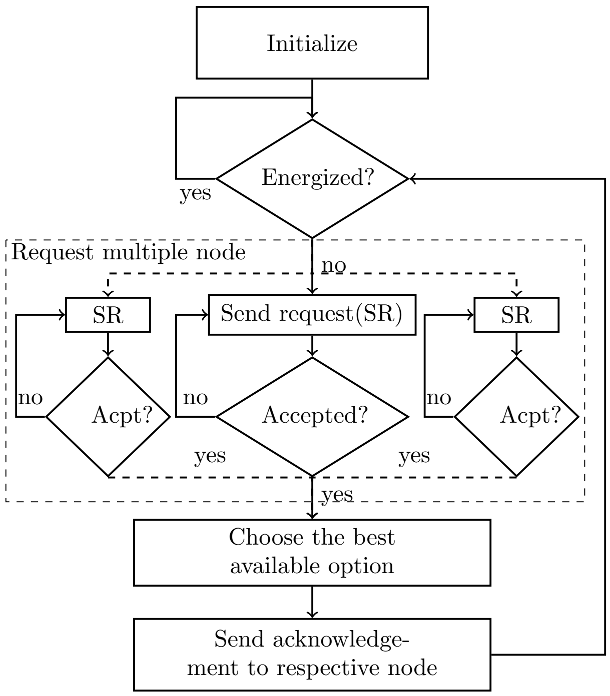


Fig. 1: Load agent(LA) state representation

- Bus agent: This is the agent who is already energized and listening for a power request. This will the negotiating part of the restorative system. It will take request from a load agent and pass it on to the generator. It will behave as a load agent to the generator as it is sending power request to it. Also, it will behave as generator agent to the load agent as it is accepting the request of power from load agents. All the intermediate bus agent behavior is to get the request from the agent it is feeding power.This information is passed to its own feeder agent which is a bus agent or generator agent from where it is getting power. This will cause a chain of information flow till it reaches a generator which can evaluate the power can be served or not. If the power request is accepted then it will relay the acceptance request in the other direction. When a bus is not energized it will behave as a load agent as it has to serve its own load that is its first priority. After it get connected at least enegizing its emergency load, it may accept power request from other load agents and it will start behaving as a bus agent. Behavior of bus agent can be described by the following figure-2

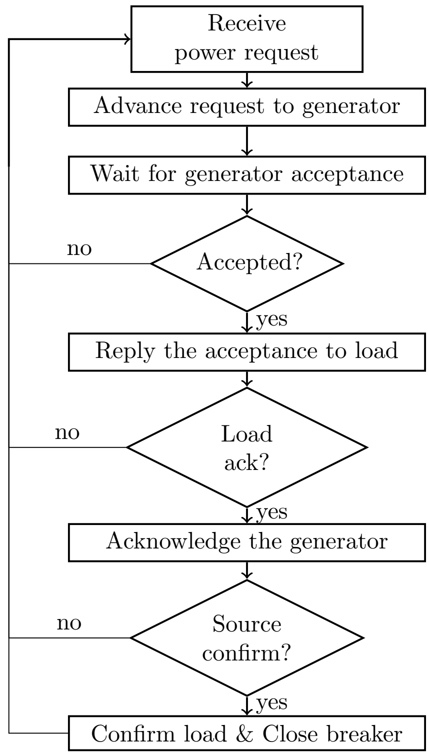


Fig. 2: Bus agent(BA) state representation

- Generator agent: This is the upper most layer of restoration agent architecture. This might be the point of common coupling for grid connected mode or a distributed generator for islanded mode. It will accept the power request from the load agent or bus agent. Then, it will evaluate if this additional power can be supplied to the bus i.e. whether it has that additional capacity or not, depending on that it will send either an accept or a reject request to the following agent. If the accept request is acknowledged in a small time interval it will assign the load to that agent and begin listening for other request. Same goes for the increment of load also. But when it is in grid connected mode generator agent behave as a bus agent with some negative load connected to it which can be assigned for a load request and each additional request is pushed up the stream as the bus agent does. Detail interaction of generator agent with other agent is explained in the figure-3

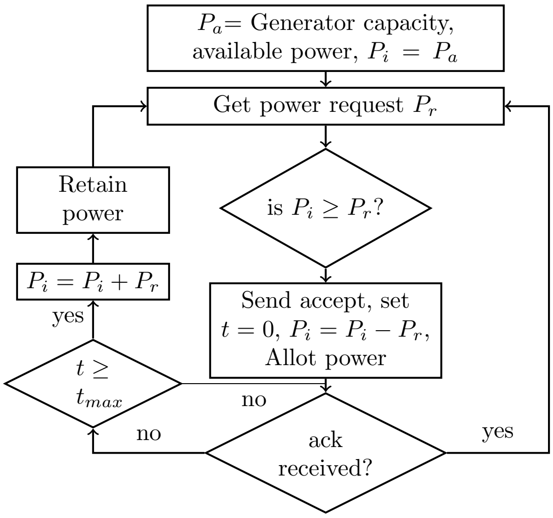


Fig. 3: Generator agent(GA) state representation

V. Agent interaction for system restoration

Restoration of a system is called upon when complete or partial blackout of the system is there. Fault location identification and system restoration will be effective when there is some criteria violation in the system. Once Fault is located and identified the system restoration begins to reform the network to bring back the system to normal operating condition. Basically restoration will be active for two scenario listed below:

A. Startup sequence

This is the scenario when there is no power at all in all the buses in power system. First the generator agent will be activated which might be the point of common coupling of the grid or a small generator for picking up the local loads. Worst case scenario is considered where non of the buses is having surplus power to provide to other buses. The network will remain always radial for ease of calculation and most of the practical distribution system are radial in nature. So the sequence of event will go as follows:

- Load agent will compose their load requirements from the smart meter reading just before fault or their forecasting mechanism for segregated loads. Load agent will start requesting the full load to nearby agent to whom it is connected to, it will set a timer at process start. If there is no reply from the neighboring agent till the time runs out it will send the request again and again.
- Generator agent will receive request from its nearest load agent and accepts the request and send back accept flag to the load while setting a timer. The moment generator sends the request it will reduce available power by the same amount requested by the load agent. If load agent do not acknowledge before timer runs out the reduced power is added back to its available power.
- On receiving the power acceptance flag from the generator agent load agent will evaluate all the option's it has to choose from. It will accept the best depending upon the voltage profile it can get when connected to the system. This will ensure minimal losses for optimal configuration and also ensures overloading of one path. Acceptance flag is replies with acknowledgement flag which starts a new timer in load agent. This flag is there only to ensure packet losses in the circuit. i.e. if there is a packet loss or the generator reset the power provided for the load due to delay it should start the handshaking process again.
- Power is alloted permanently to the load agent on receiving the acknowledgement flag. This time there is no timer for any reply information. But the final acknowledgement acceptance flag is sent back to the load agent. This is the time when generator agent will close the breaker connecting to the line connected to load agent.
- Load agent will close its breaker on receiving the acknowledgement acceptance and resets the timer initially started. If there is a packet loss in between the last step, it will request again to the generator for power which is preallocated so generator agent will only see the differential and won't allot any power but will send the acceptance. This is to ensure no double allocation for the same load is done.
- Load agent which is energized can be a medium to connect to the generator. So this will behave as a bus agent from this moment onwards. All the other buses connected to it, which are not connected to generator directly can request power to this agent. For the neighboring unenergized load agent this is an generator agent.
- Generator agent will accept request and the same process will go on till the last load is energized or the limit of generator to provide load is exceeded. There might be some cases where the limit of transmission line exceeded to provide load in the required voltage profile which is not yet been seen in the simulation work.

B. Partial load pickup

Partial load pickup is active a line or a bus fault occurs. Here selection of line plays more vital role than startup sequence. During startup occurrence of more than one energized line in the transfer path is rare because the whole system is picking load and will take some time to energize all the neighboring loads. But in partial load pickup most of the neighboring line are energized so selection is a crucial part for efficient and optimized solution. The chain of event is will go as follows:

- As soon as we detect there is no power in specified bus or load, the restoration agent starts its requesting procedures. As there is fault in the previous path the agent will reject the request.
- Healthy buses nearby will accept the request and forward the same to the preceding agent.
- The moment it reaches to a generator agent it will accept or reject depending the capacity of the agent. This will then initiate an power accept request toward the bus agent.
- On acceptance of the power from generator agent, bus agent will calculate the incremental voltage drop due to

the extra load to the preceding line. This information along with the acceptance of power is forwarded onwards.
- Based on the voltage drop next agent will calculate its own voltage level post energization of the new load. This process will be forwarded till it reaches the load end.
- Then depending on this voltage and power acceptance information load agent will decide which node or agent to choose from for best voltage profile. It will initiate an acknowledgement after the selection process is over.
- The same handshaking as described before will go on till the load is energized and both breakers from load and generator end is closed after negotiation.

VI. Selection of communication system

In this simulation author has taken ethernet as communication medium however changing the communication channel will not change the behavior of the work. The delay in communication channel may vary depending on the medium but these delay can be ignored considering other higher time constants in power system viz. breaker closing time, response time for restorative agent and so on. For data transfer ipv4 is selected, as it is popularly used Internet protocol. This protocol provides rules for packet transfer between hosts and clients.

TCP is used for data exchange between hosts. As TCP confirms delivery of packets while keeping the packet sequence intact, this is one of the best protocol for multi agent system data exchange.

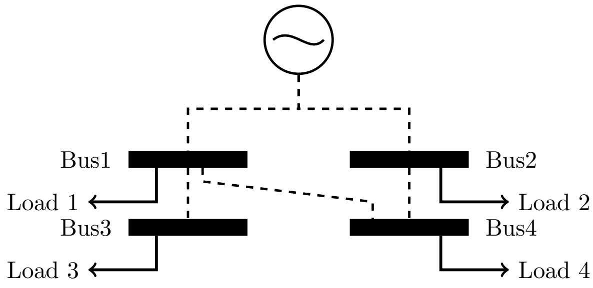
As these protocols are independent of the medium we can change the medium depending on the availability and cost of implementation. For well connected urban area we can use the same without any changes but for remote ends it is a very costly option to implement wires upto that point. For remote agent, which is very rare in this kind of scenario, we can go for 3G or 4G communication which also supports TCP/IP for data transfer. Any other protocol which support the above mention criteria will also suit best for these functions.

VII. Simulation and results

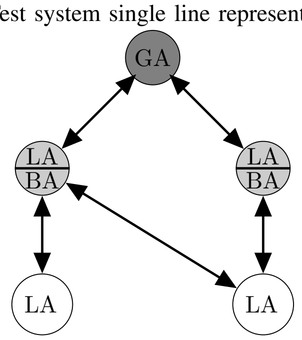
The selection of programming language should be such that it can be implemented with lowest of hardware requirements and the cost of implementation should be low. Ease of programming also is selection criteria for the programming language adoption in different scenarios. Based on the above criteria Python is used for the entire work. Availability of single board computer are on the rise with linux distribution on it, all of which support python out of the box, which is an excellent way to go for low cost multi agent system. The entire simulation is test on a dual core machine which is having 2GB RAM.

Multi threaded option of python programming is exploited to create multiple listening ports for the generator agent. This will give us the means to listen to many request at the same time which in turn reduces the restoration duration. Sending of a request is however no parallel. Parallel request from single node may confuse the receiving end agent about how much power increment is required to that node, there might be multiple method to handle that, this is not implemented in the present work.

The system under consideration is however a very small system having 5 nodes with one serving as a generator and the rest serving as loads. connection diagram is given in the below figure-4a. Each bus needs 150KW, 160KW, 165KW and 145KW respectively.



(a) Test system single line representation



(b) Agent representaion of the system

CASE-I: *S*tartup sequence

A detailed startup sequence is shown by the following figure-5 for better understanding of how the simulation works.

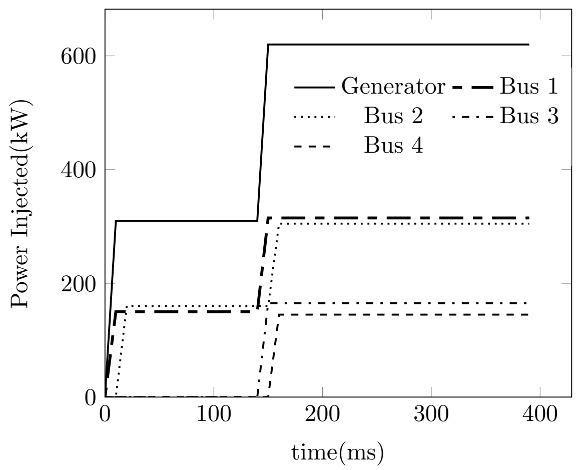


Fig. 5: Test system single line representation

Here we can notice that power assignment of bus1 and bus2 by the generator is few mili seconds before the load pickup by the bus1 and bus2. This is the duration of handshake at which the power is assigned and the acknowledgement will be done on both the side. Both the load from bus1 and bus2 are picked up at the same time which shows the multi threading support of the program. This show that it can accept multiple request at the same time and assign power to two different agent if sufficient power is available.

Once the preceding buses to bus3 and bus4, i.e. bus1 and bus2, are energizes now bus agent will behave as generator agent and can accept power. This will then be forwarded to generator agent. We can see the delay between accepting power of the generator and the handshaking delay once again here. First the assignment of generator power is done then the power is assigned at bus1 and bus2.Lastly the bus3 and bus4 , both of which are load agent as there is no bus after that, will close the breaker and get the allocated power.

CASE-II: *P*artial restoration

Let us consider there is a fault in bus2 during normal operation. Protective system will detect the fault and remove bus2 from operation and maintenance. The behavior of load agent 4 which was supplied from bus agent 2 is shown in the following figure-6.

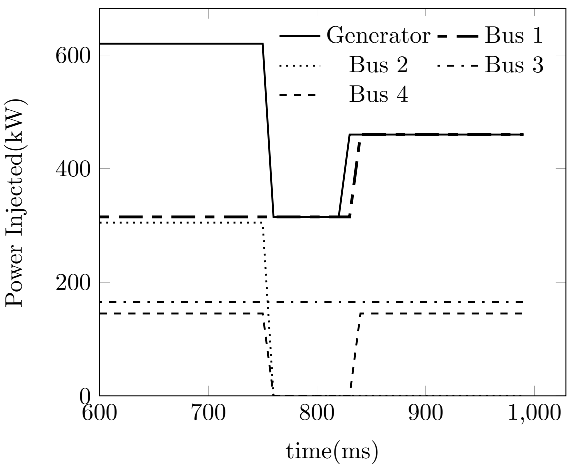


Fig. 6: Test system single line representation

As soon as the bus2 is removed from the service load at both bus2 and bus4 will not be served. As bus2 is th faulted bus we can not do anything to that bus till the fault is cleared and it is back on line. But bus4 agent is running and active which will start requesting power from other paths. Bus2 will not give any reply as it is turned off. The only reply it will get is from bus1, it will wait for the timer to go off. If there is no reply from bus2 it will accept the power from bus1 without any selection process. We can see now the entire load is carried by bus1.

VIII. Conclusion

This work shows that a multi agent system can easily be implemented in the system which will increase the efficiency of restoration while increasing the reliability of the system. Complete autonomy can be achieved using multi agent system which will self heal post disturbance without human intervention. However its behavior for very large systems are yet to be seen. The aspect of restoration using multi agent system in a meshed network is under studies for further increase in efficiency of the system.

References

[1] C.-C. Liu, S. J. Lee, and S. Venkata, "An expert system operational aid for restoration and loss reduction of distribution systems," *Power Systems, IEEE Transactions on*, vol. 3, no. 2, pp. 619–626, 1988.

[2] S. Siqing, S. Youjiang, L. Yan, Z. Wenqin, and Y. Yihan, "Integrating genetic algorithm with expert system for service restoration in distribution system," in *Power System Technology, 1998. Proceedings. POWERCON'98. 1998 International Conference on*, vol. 1. IEEE, 1998, pp. 265–269.

[3] Y.-Y. Hsu and H.-M. Huang, "Distribution system service restoration using the artificial neural network approach and pattern recognition method," *IEE Proceedings-Generation, Transmission and Distribution*, vol. 142, no. 3, pp. 251–256, 1995.

[4] J. McElray Sr and V. Gharpure, "Loop control schemes increase restoration," in *Transmission and Distribution Conference and Exposition, 2001 IEEE/PES*, vol. 1. IEEE, 2001, pp. 171–176.

[5] R. Pérez-Guerrero, G. T. Heydt, N. J. Jack, B. K. Keel, and A. R. Castelhano, "Optimal restoration of distribution systems using dynamic programming," *Power Delivery, IEEE Transactions on*, vol. 23, no. 3, pp. 1589–1596, 2008.

[6] S. Kazemi, M. Fotuhi-Firuzabad, M. Sanaye-Pasand, and M. Lehtonen, "Impacts of automatic control systems of loop restoration scheme on the distribution system reliability," *Generation, Transmission & Distribution, IET*, vol. 3, no. 10, pp. 891–902, 2009.

[7] F. Ding and K. A. Loparo, "A simple heuristic method for smart distribution system reconfiguration," in *Energytech, 2012 IEEE*. IEEE, 2012, pp. 1–6.

[8] J. M. Solanki, S. Khushalani, and N. N. Schulz, "A multi-agent solution to distribution systems restoration," *Power Systems, IEEE Transactions on*, vol. 22, no. 3, pp. 1026–1034, 2007.

[9] A. Saleem and M. Lind, "Requirement analysis for autonomous systems and intelligent agents in future danish electric power systems," *International Journal of Engineering, Science and Technology*, vol. 2, no. 3, pp. 60–68, 2010.

[10] G. L. Clark, "A changing map: Four decades of service restoration at alabama power," *Power and Energy Magazine, IEEE*, vol. 12, no. 1, pp. 64–69, 2014.

[11] P. Li, B. Song, W. Wang, and T. Wang, "Multi-agent approach for service restoration of microgrid," in *Industrial Electronics and Applications (ICIEA), 2010 the 5th IEEE Conference on*. IEEE, 2010, pp. 962–966.

[12] A. S. Rao, M. P. Georgeff *et al.*, "Bdi agents: From theory to practice." in *ICMAS*, vol. 95, 1995, pp. 312–319.