GRAPH THEORY AND PARTICLE SWARM BASED RECONFIGURATION OF MULTIPLE MICROGRIDS FOR GRID RESILIENCY

By

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GRAPH THEORY AND PARTICLE SWARM BASED RECONFIGURATION OF MULTIPLE MICROGRIDS FOR GRID RESILIENCY

Abstract

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The ability to increase the reliability and resiliency in power distribution system is a fundamental reason for the high penetration of multiple microgrids. Multiple microgrids provide a possibility for a microgrid to transfer power to another microgrid in the same cluster through reconfiguration in case of power loss to loads.

In this thesis, a reconfiguration formulation for multiple microgrids to maximize the energized loads considering load priority and resiliency requirements is formulated. The proposed solution for this reconfiguration formulation is developed using a two-stage algorithm. After the unsupplied loads are identified, the restoration process is continued based on the type of loads. The unsupplied priority loads are restored using the path search algorithm, while the unsupplied non-priority loads are restored using the modified adaptive particle swarm optimization. Both of the approaches are based on graph theory. Testing and validation of the developed algorithms is performed using the following test cases: 1) one microgrid is islanded after the fault, 2) a fault within a microgrid leading to load loss, and 3) a fault within a microgrid

when two microgrids are islanded. A power flow calculation is used to verify if priority and non-priority loads have been restored without violating any constraint. The CERTS microgrid is used as the model for every individual microgrid and MATLAB is employed as the simulation platform.

The results show that the developed algorithm is able to maximize the number of energized loads after faults and minimize load loss, while ensuring minimum switching, maximum DER utilization, and open-loop topology. Based on these results, it can be concluded that the reconfiguration formulation and the developed two-stage algorithm can successfully transfer power between microgrids in the same cluster to maximize the load restoration.

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CHAPTER ONE: INTRODUCTION

1.1 INTRODUCTION

Continuous power supply to the customer is the most important aspect to maintain high power system reliability and resiliency. Learning from the previous massive blackouts, electricity generated by the large scale power plants located in places far from the customers is identified as one of the main causes of failure in a power system. One of the solutions proposed to create a more reliable power system is the distributed energy resources. The penetration of distributed generation in power systems is expected to help avoid the impact of a large blackout in a power system. Following the distributed generations plan, the concept of the microgrid was introduced to isolate the part of the system from main grid in emergency and use the local generation. As defined in the U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability Smart Grid R&D Program's 2012 DOE Microgrid Workshop Summary Report, a microgrid is “A group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid [and can] connect and disconnect from the grid to enable it to operate in both grid-connected or island mode” [1].

In addition, integrating microgrids into distribution system is beneficial in increasing grid resiliency. Whether caused by nature or human action, resiliency is defined by National Infrastructure Advisor Council (NIAC) as the "ability to reduce the magnitude and/or duration of disruptive events"[2]. During these abnormalities, the integration of microgrid contributes to power system resiliency through its ability to support their own critical loads and community critical loads as well as to act as a black start resource [3]. In this thesis, the contribution of multiple microgrids reconfiguration to improve grid resiliency by supporting the community priority loads, which are in other microgrid(s) in the same cluster, are presented.

The multiple microgrids concept is defined as a cluster of multiple neighboring microgrids, but not necessarily connected to the main power grid via the same substation or feeder. The multiple microgrids within the same cluster are expected to support each other in the event of faults and disturbances by the switching operation. For example, when a fault occurred between the main power grid and microgrid MG_i, MG_i then operates in islanding mode and loses 30% of its power supply. It is expected that by closing the tie switch between MG_i and microgrid MG_j, these two microgrids in the same cluster could exchange power to maximize the number of energized loads at MG_i. It is also expected that the open-loop topology of the system will be reserved by opening certain sectionalizing switch(es) at both microgrid MG_i and microgrid MG_j to meet the protection requirements. Reconfiguration for multiple microgrids will also help to provide a business model and to exchange power to maximize the economic benefits.

1.2 OVERVIEW OF RECONFIGURATION FOR MULTIPLE MICROGRIDS

Reconfiguration for multiple microgrids in this thesis aims to restore power to the loads in the case of outage due to fault or disturbance in the system. Although, reconfiguration algorithms with objective of load restoration in power distribution system and microgrid system have been investigated well by several researchers, not much work has been done for multiple microgrids reconfiguration. Through observations on microgrid operations, especially the ones with high penetration of non-controllable Renewable Energy Sources (RES), such as photovoltaic panels and wind turbines, it may be possible that RES generates less power than required, for example due to lack of sunshine. At another time, during the scheduled maintenance of one or two large-scale RES units, the power imbalance may occur in the microgrid. With the assumptions that each microgrid is not supported by large Energy Storage System (ESS) and in a case that connection to main grid is impossible due to abnormal event or fault in the main grid side, a strategy to maintain critical loads to be continuously supplied is critical to be developed. With the increasing penetrations of microgrids into power distribution system, it is possible to group several neighboring microgrid into the same cluster, with normally open switches connecting two microgrids. By this group of neighboring microgrids in a cluster, a power exchange from one microgrid with surplus power to another microgrid with deficit power within the same cluster is expected to benefit the microgrid operation, indicated by an increasing reliability and resiliency.

In comparison to the traditional power distribution reconfiguration, the microgrid reconfiguration may result in a group of DER and loads operating separately from the original microgrid system. Similarly, it is expected that in the multiple microgrids reconfiguration, one or more loads from a microgrid can be transferred to another microgrid in the cluster (load exchange). It is also possible that a load from a microgrid may be transferred to another feeder or RES of another microgrid and this group of generation and load(s) then operates separately from any initial microgrids. Depending on how one wants the load restoration to reconfigure the topology of its microgrid cluster, several rules can be developed for the multiple microgrids reconfiguration action. As emphasized in [4], there is no single rule applicable for the restoration action in multiple microgrids environment. Diverse MV network characteristics, including types of energy sources used, power electronics interfaces, and loads, distinguish the restoration actions must be taken to bring the unsupplied loads of a certain multiple microgrids cluster back into the operation. Hence, several specific assumptions are taken in this thesis work, they are 1) the presence of non-controllable type RES as the only distributed generation units, 2) the presence of non-priority load in every feeder, 3) the absence of energy storage systems, and 4) the absence of islanding operation of a group of RES and loads created from the original microgrids in the cluster.

1.3 MOTIVATION FOR RESEARCH WORK

Several research works related with multiple microgrids operation have been reported. The topics are ranging from the energy management systems and control strategy for integration to or disintegration from the main grid, hierarchical control in multiple microgrids, energy exchange between microgrid and main grid, multiple microgrids communication systems, multiple microgrids protection scheme, and multi-agent coordination. However, considering the increasing number of microgrid installed in the power distribution system, there are still limited works reported in reconfiguration strategy of multiple microgrids.

In addition to the limited research on multiple microgrids reconfiguration, the important goal of multiple microgrids reconfiguration in increasing the reliability and resiliency of power distribution system as elaborated in Section 1.2 motivates to perform research in the reconfiguration strategy, specifically for load restoration purposes in multiple microgrids environment for higher grid resiliency.

To find the optimum solution for the reconfiguration problem, most strategies nowadays are based on iterative methods, which use combinations of different variables and exploring the solution spaces. As the search space is usually large, iterative method needs some time to find the optimum solutions. However, there is no guarantee that the optimum solution could be successfully found (e.g., the optimization could be trapped in local optimum or the problem formulation creates a non-convergence search space). Further, when the number of non-priority loads in a power system is much more than the number of priority loads, the possibility of non-convergence for non-critical load becomes higher. This is in contrary to the concept of resiliency in power systems, where fast recovery to the priority loads is more crucial than optimal solutions. Hence, this thesis aims to speed up the process of reconfiguration, especially for priority loads, by developing an algorithm that avoids the tedious iterative process.

1.4 THESIS OBJECTIVE

The concept of multiple microgrids reconfiguration aims to study how connecting two or more neighboring microgrids in the same cluster will help to minimize the load interruption for higher resiliency, while taking open-loop topology and load priority into the consideration. This thesis aims to:

- Develop a reconfiguration formulation for multiple microgrids using a modified CERTS microgrid to maximize the energized load considering load priority and resiliency requirements
- Develop the solution techniques to solve the reconfiguration formulation in multiple microgrids using two-stage algorithm
- Test and validate developed algorithms using multiple microgrids case studies

1.5 THESIS ORGANIZATION

This thesis is organized into five chapters.

The first chapter introduces the scope of the research work, the overview of the reconfiguration in multiple microgrids, the motivation for the research work, the objective of the research work, and the organization of the thesis.

The second chapter presents the related works in distribution system reconfiguration. The concept of microgrid, multiple microgrids, and related works in both microgrids are also presented. The chapter ends with a discussion on the research gap that motivates this thesis.

The third chapter addresses the problem formulation and solution approach of the research work, including the main goals to be achieved, the objective functions, and the operation constraints. The priority loads restoration using path searching algorithm and the non-priority loads restoration using Particle Swarm Optimization (PSO) as the two stages solution method are also detailed in this chapter.

The fourth chapter reports the simulation results, including test cases and the assumptions. The simulation is performed using MATLAB, and the results as well as the discussion are presented at the end of this chapter.

The fifth and last chapter concludes the research work and suggests possible future research.

1.6 SUMMARY

This chapter introduces the research work addressed in this thesis. Brief introduction to microgrid and multiple microgrids concepts have been presented, followed by the introduction to reconfiguration in distribution systems. The motivation and the objectives of the research work are also explained. Finally, the thesis organization is presented.

1.7 REFERENCES

[1] Office of Electricity Delivery and Energy Reliability, "Summary Report: 2012 DOE Microgrid Workshop," U.S. DOE, Chicago, IL, 2012.

[2] A.R. Berkeley III and M. Wallace, "A Framework for Establishing Critical Infrastructure Resilience Goals," National Infrastructure Advisory Council, Arlington, VA, Rep., 2010.

[3] K. Schneider and C.C. Liu. (2014, Jun 6). Smart Grid R&D Program Peer Review Meeting (2014) [Online]. Available: http://energy.gov/oe/downloads/2014-smart-grid-rd-peer-review-day-one-session-two.

[4] N. Hatziargyriou, "Operation of Multi-Microgrids," in Microgrid: Architectures and Control, 1st ed. West Sussex, United Kingdom: WILEY, 2014, ch. 5, sec. 5.5, pp. 186-192.

CHAPTER TWO: BACKGROUND

2.1 INTRODUCTION

A distribution network reconfiguration (DNR) with priority to critical loads is considered as one of the important contingency plans to improve power system resiliency. It is also related with the operational cost that the utility company may lose when the generated/purchased power cannot reach the customers as intended [1]. This chapter starts by describing the concept of resiliency in power distribution systems. Then, the concept of DNR and the solution approaches, specifically the reconfiguration to recover a load are discussed to introduce the same work in microgrid and multiple microgrids environment. The discussion of reconfiguration in microgrid and multiple microgrids are discussed as well as detail description of the model used in this thesis. After previous power reconfiguration works in distribution network, microgrid, and multiple microgrids are discussed and compared, this chapter is concluded by presenting the gaps in reconfiguration research in multiple microgrids environment.

2.2 RELATED WORK IN DISTRIBUTION SYSTEM RECONFIGURATION

Following the event of Hurricane Sandy back in 2012, the topic of resiliency in power system became more critical. A resilient infrastructure, as described by NIAC in [2], relates with the "ability to anticipate, absorb, adapt to, and rapidly recover from a potentially disruptive event". In power systems, resiliency deals with power imbalance, which means there is not enough power to loads. Hence, power systems are required to have such abilities through planning ahead, operating, and protecting the system from a disruptive event. Resilient power systems also must have security priority [3] and fast recovery [4] criteria as its key elements. In addition, resilient power distribution systems must inherit the following properties: prevention, survivability, and recovery [5]. This thesis focus only on the recovery of power distribution systems, by providing reconfiguration plans which satisfying the security priority and fast recovery criteria.

The concept of reconfiguration is closely related with switching options [6]. The reconfiguration requires mapping for switch status (OPEN or CLOSE) to achieve different objective in power system operation. The two commonly used objectives in the DNR are load restoration and loss minimization. Both objectives could also be combined as multi-objective reconfiguration as presented in [7-10]. If the main purpose of the reconfiguration action is to restore power to the load when a fault or disturbance happens, the mapping of switches is obligated to minimize the outage area or in other words to maximize the number of energized loads in minimum time. Shifting the pressure of control room operators during emergency condition is also an expected outcome of reconfiguration plan for power restoration [11-14]. If the main purpose of the reconfiguration action is the loss minimization, the mapping of switches is obligated to choose the path to deliver the power to customer loads with the minimum total loss during normal operating conditions. In the end, by delivering electricity to customer through the best path, the production and operation costs could be minimized, and system reliability and stability could be improved as well [15-19]. It is also important to note that any reconfiguration action, whether for load restoration or loss minimization, has to satisfy the operation constraints as well as maintain the open-loop topology of distribution systems [12,13].

The distribution network reconfiguration has widely been researched since the 1980's [20]. Many methods have been introduced and evaluated. As discussed in [20], the methods are categorized as the traditional mathematics algorithm and artificial intelligence algorithm. The traditional mathematics algorithms include the linear programming, and non-linear programming, such as Newton method, Inner point method, etc. Some examples of reconfiguration work using the artificial intelligence algorithms are using evolutionary algorithm as reported in [21], using genetic algorithm as reported in [22,23], and using particle swarm optimization as reported in [6, 14, 19, 24]. Other than these methods, several research works are based on the heuristic methods as reported in [15,25].

2.3 RELATED WORK IN MICROGRID

2.3.1 Microgrid Concept and Definition

In comparison with the definition of a microgrid by U.S. Department of Energy presented in Chapter 1, a task force of microgrid research in European Union [26] presented the following definition: "Microgrid comprise LV distribution systems with distributed energy resources (microturbines, fuel cells, PV, etc) together with storage devices (flywheels, energy capacitors and batteries). Such systems can be operated in a non-autonomous way, if interconnected to the grid, or in an autonomous way, if disconnected from the main grid. The operation of micro-sources in the network can provide distinct benefits to the overall system performance, if managed and coordinated efficiently." By understanding both definitions, the following are the main characteristics of a microgrid [26]:

i) A microgrid involves high penetration of DER with interconnected load, and energy storage devices (if applicable)

ii) A microgrid has the ability to connect and disconnect from the main grid or in other words, a microgrid is able to operate in grid-connected and island mode

iii) A microgrid is equipped with management and control to manage its system

In the case that DER is absent or load is absent or monitoring and control are absent or there is no ability to isolate itself from the main grid, a small-scale power system cannot be classified as a microgrid [26]. In addition, a microgrid may represent a power system in different size, such as grid level microgrid, feeder level microgrid, and house or building level microgrid. The basic objectives of microgrid are to improve reliability and resiliency, to promote high penetration of renewable sources, to enable dynamic islanding, and to improve efficiency via the use of waste heat [27].

A microgrid offers a wide range of benefits, starting from commercial benefit, technical benefit, and environmental benefit. Commercially, by having a microgrid, an end customer may have an opportunity to buy electricity at prices lower than retail prices, while the DER owner may have an opportunity to sell at the price higher than wholesale level. Technically, microgrid will have major contribution for the reduction of peak loading, voltage variation, and system loss as well as for the improvement of reliability index. Also, as microgrid concept was introduced to accommodate the higher penetration of small scale DER, it will contribute to the environment through total emission reduction [26]. In addition, an integrated microgrid to distribution systems also has a benefit in increasing systems' resiliency by supporting their own critical loads as well as community critical loads, and acting as a black start resource [5]. This thesis focuses on the impact of microgrid in supporting critical loads by performing reconfiguration.

CERTS Microgrid Concept

In this thesis, the CERTS microgrid concept [28] is used as the model. The CERTS microgrid concept has two critical components and six protection zones. The two critical components are static switch (SS) and DER. The SS is responsible to separate the DER and priority loads zones from the main grid in the case of disturbance. DER is responsible to generate power for all loads in a microgrid. The six protection zones are shown in the single line diagram of a CERTS microgrid as shown in Figure 2.1. The main grid or utility is named Zone-1, while the zone that includes SS and has a function to separate the DER from the main grid is named Zone-2. SS serves two different feeders. The first feeder consists of Zone-3 and Zone-4, which have DER and serve priority loads using a four-wire cable. The second feeder consists of Zone-5 also has DER and priority loads, but it is supplied through three-wire cable and an isolation transformer. Zone-6, consisting of non-priority loads, is connected to the main grid at all times [28].

A Modified CERTS Microgrid used in This Thesis

A modified CERTS microgrid is used in this thesis. The main reason behind this modification is to facilitate the simulation of load restoration. The modification does not change either the way microgrid operates or the simulation results.

The modifications made to CERTS microgrid in this thesis are including removing substation transformer between main grid and the microgrid, changing the cable of Zone-3 and Zone-4 to be three-wired, removing the isolation transformer from Zone-5, and relocating the loads in Zone-6 into the inner part of SS protection zone. In addition, the RES in Zone-3, 4, and 5 serve not only priority loads, but also non-priority loads. This modified system is presented in Figure 2.2. Further to this modification, several scenario-based assumptions are taken to make the simulation more attractive and will be explained in each case study in Section 4.3

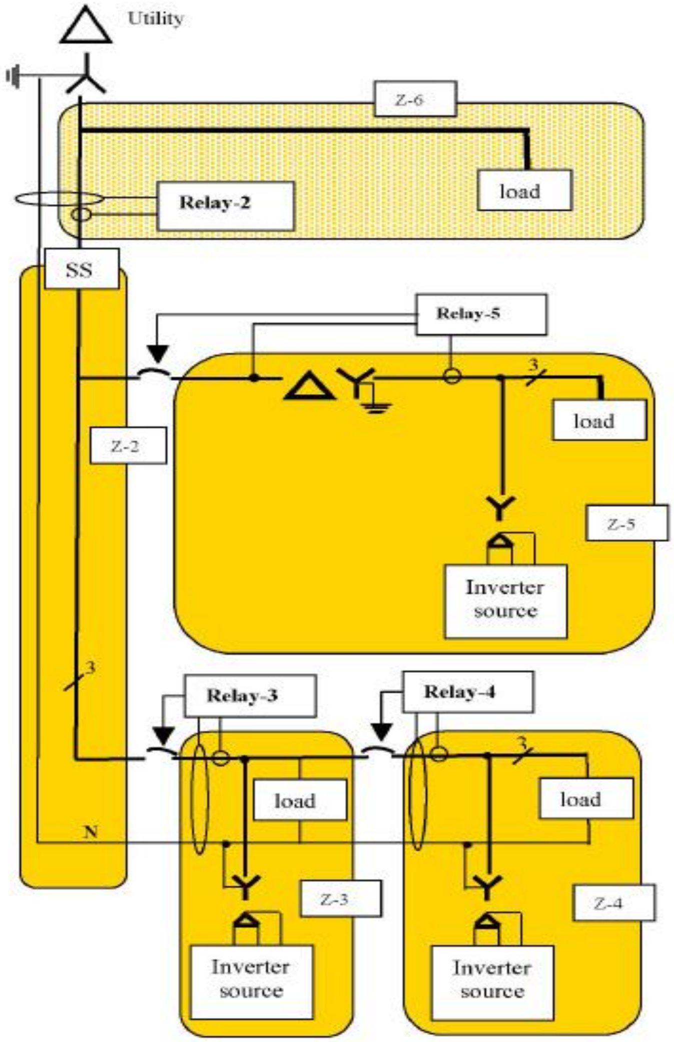


Figure 2.1 CERTS Microgrid [28]

2.3.2. Reconfiguration in Microgrid

Along with the emerging integration of microgrids into power systems in many countries, such as Germany, United States, Japan, and China, more research related with optimization of microgrid operation are conducted. Initially, microgrid researchers paid more attention on the integration and separation process from the main power grid, but eventually there are more works conducted in the area of microgrid reconfiguration. Similar with DNR, most of

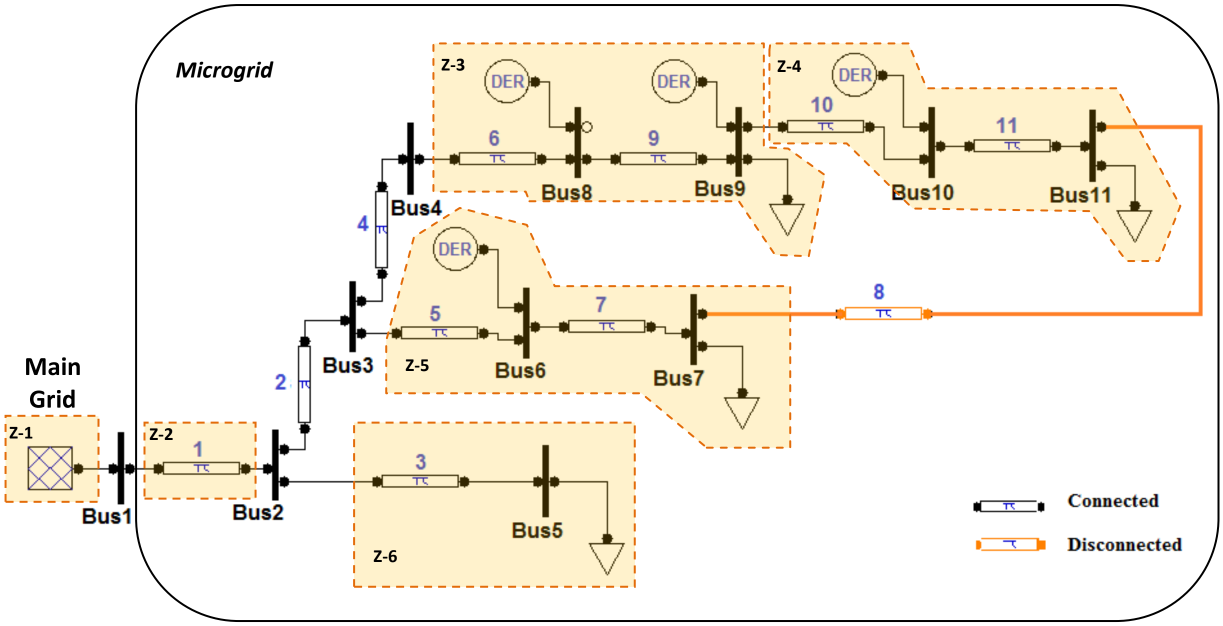


Figure 2.2 The Modified CERTS Microgrid

reconfiguration research in microgrid reconfiguration aim at power losses minimization and maximum load restoration following a fault or disturbance event as shown in [23, 29-35].

Due to its micro scale power capacity, a microgrid is usually covering a small load service area. In other words, the distance between distributed energy resources to the loads in the microgrid system is usually much smaller compare to the traditional distribution network. Considering this fact, one will tend to conclude that the power loss in a microgrid is less than the traditional distribution network. However, it is very important to evaluate some other parameters before jumping to this conclusion. As discussed in [29], the low operating voltage is one of the parameter causing a microgrid to have the high resistance loss. For a microgrid equipped with Energy Storage System (ESS), as presented in [30], the non-optimized sizing and placement of ESS is the potential cause of significant power losses in microgrid system. However, an interesting work using subgradient optimization is presented in [31] to prove that microgrid ability to maintain unified voltage profile will result in the active power losses minimization. An example of reconfiguration work with an objective to minimize power losses in a microgrid is discussed in [30]. Using Particle Swarm Optimization (PSO), this reconfiguration decides the optimal location of ESS to achieve the objective.

The distributed energy resources (DER) located at a microgrid provides a strong contribution in restoration of the unsupplied load. When a fault occurred in the upstream part of traditional distribution feeder, all loads located at the downstream experience power outage until this fault is removed. With the existence of DER and the ability to connect and disconnect from the main grid, a microgrid is able to keep the downstream loads to be continuously supplied; hence, the outage area is minimized. In [13], this ability is described as a self-healing ability and is beneficial in minimizing the overall downtime in distribution system. This is the main difference between load restoration in microgrid and the traditional distribution system as well as a benefit of the microgrid penetration into distribution system.

The solution approach, however, is very similar to the solution approach of power restoration in DNR. Several works such as presented in [23, 32, 33] employed genetic algorithm to solve the microgrid reconfiguration work in order to restore the maximum number of loads. While the work in [32] emphasize that the fault recovery work is also aimed to reduce the number of switching operation, the work in [23, 33] paid more attention on achieving the maximum number of supplied load based on the load priority. Another work in [34] used the ordered binary decision diagram (OBDD) to solve the microgrid reconfiguration in the event of catastrophic failure of the main power grid. The main objective of this work is to minimize the cost of load loss. One of the solution methods that is widely used in microgrid operation research is the Multi-Agent System (MAS). In [35], a novel MAS algorithm based on Average Consensus

Theorem is used in the microgrid reconfiguration to achieve maximum number of load supplied. This algorithm has three advantages compared to the previous work using MAS, they are a rigorous stability algorithm, a scalable algorithm, means this algorithm is applicable for different power system configurations and sizes, and an improvement in parameter setting algorithm that is used for adjusting the coefficients of exchanged information.

2.3.3. Overview of Multiple microgrids

With the increasing penetration of microgrids in distribution systems, the concept of multiple microgrids is introduced by the EU More Microgrids project as reported by J.A Pecas-Lopes in ‘Advanced Architectures and Control Concepts for More Microgrids’ on 2007. In this project, the concept of multiple microgrids is introduced as the solution to the limited load capacity in an individual microgrid [36]. The concept of multiple microgrids is formulated in [37] as "a high-level structure, formed at the medium voltage (MV) level, consisting of several LV microgrids and distributed generation (DG) units connected to adjacent MV feeders." Multiple microgrids concept is described in Figure 2.3.

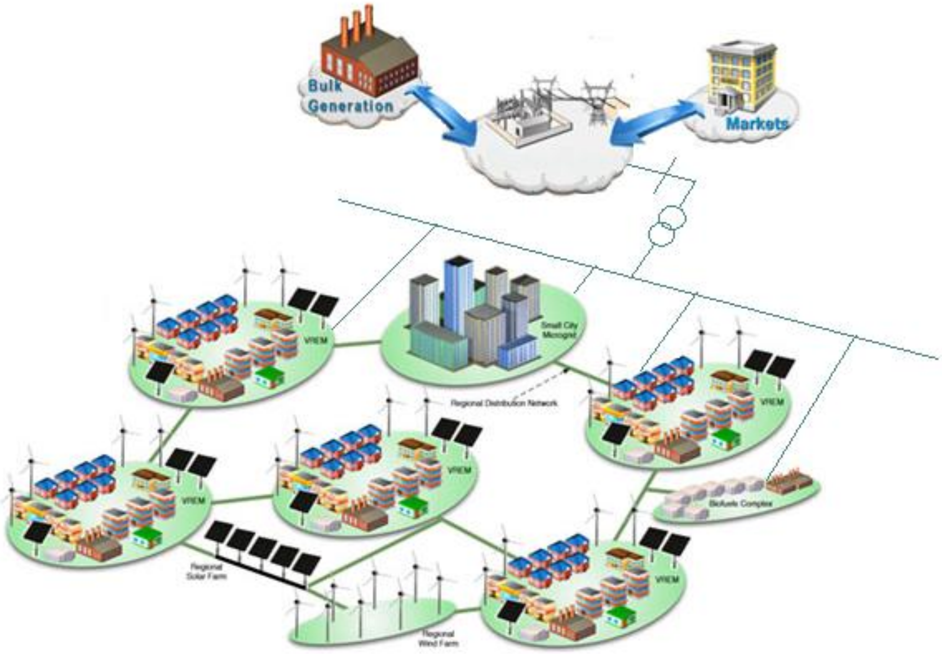


Figure 2.3 Multiple Microgrids Concept

In addition, by having multiple microgrids in the same clusters, it is hoped that in the event of faults and disturbances, after a sequence of switching operations, these microgrids will be able to support one another. Another goal of multiple microgrids is to increase the reliability of each microgrid in the cluster, especially when getting any support from the main grid is not an option. For example, when a fault occurred between the main power grid and microgrid MG_i, MG_i loses 30% of its power supply, which previously received from main grid and has to change its operation mode into islanding for fault isolation purpose. However, since MG_i is in the same cluster with MG_j, MG_i now has an alternative to get support from MG_j (completely or partially) by closing the tie switch(es) in between. If MG_j is able to transfer power in order to support MG_i, then these two microgrids could then operate continuously. This means the number of energized loads at MG_i during the fault condition can be maximized.

The Multiple microgrids discussed in this Thesis

The multiple microgrids evaluated in this thesis consists of two individual microgrids based on CERTS microgrid presented in Section 2.3.1. Both microgrids are connected to the main grid through different feeders, but the same substation. Two different microgrids are separated/connected by a tie switch. The single line diagram of the multiple microgrids used in this works is shown in the following Figure 2.4.

Further to several assumptions on modified CERTS microgrid used in this thesis, the following assumptions and conditions are also applicable for the multiple CERTS microgrid model. This work relates to only steady-state analysis, with main grid and RES are treated as a constant three-phase AC voltage sources. Specifically for the RES, the three-phase AC voltage is the one measured at the output of the inverter. The Static Switch (SS) covers not only the priority loads and RES, but also the non-priority loads. There are two priority load feeders in this model. A tie switch connecting both feeders is provided at the end of each feeder to enhance the reliability index of priority loads. The non-priority load feeder, on the other hand, is not connected to any other feeder. For a connection between microgrids in the same cluster, a tie switch is provided at the end of a priority load feeder. The tie switch is only provided at the end of priority load feeder to indicate the higher importance of load in these feeders.

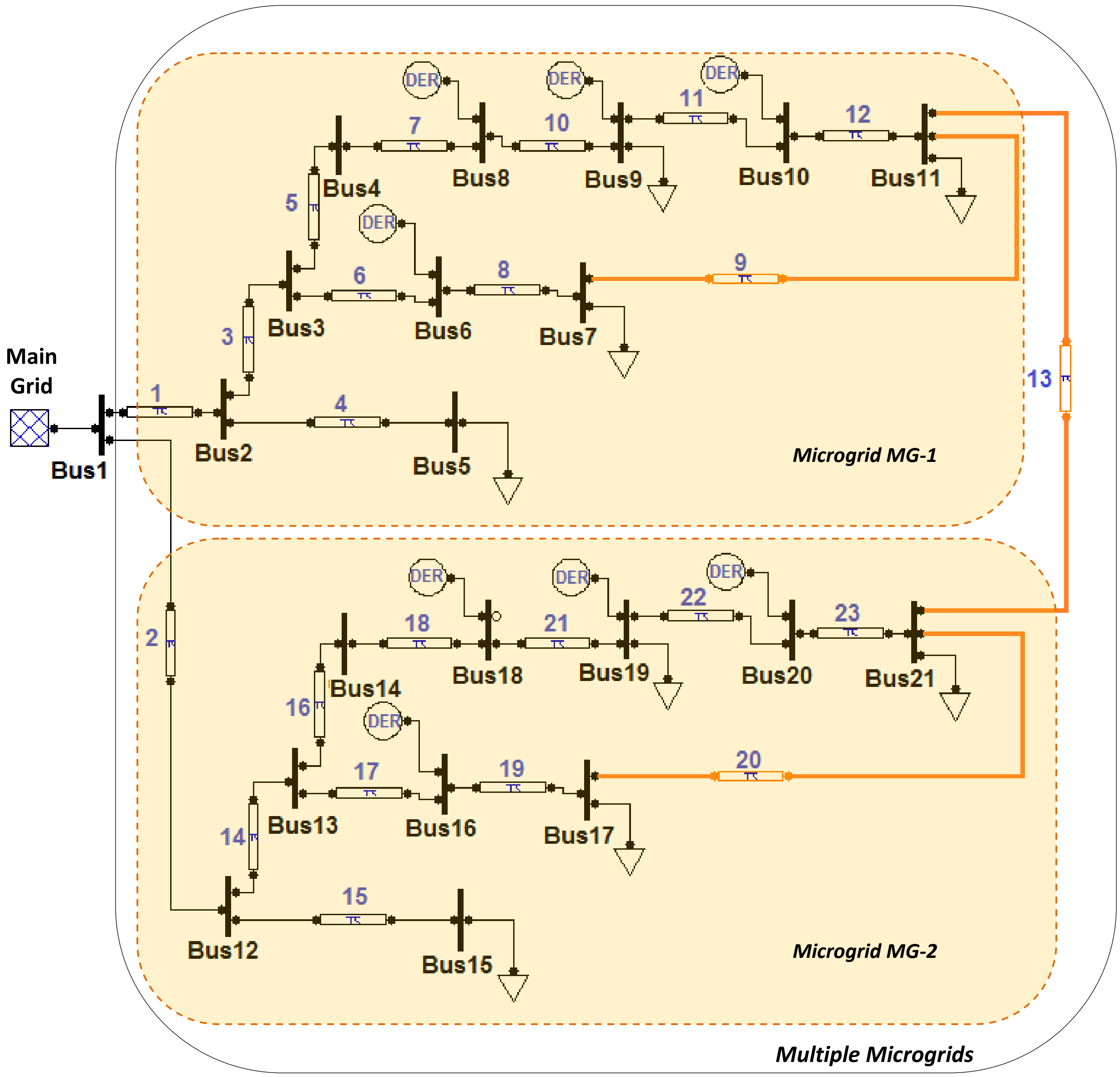


Figure 2.4 Multiple microgrids based on CERTS Concept

2.4 RECONFIGURATION IN MULTIPLE MICROGRIDS

Since the concept of a multiple microgrids was introduced by the EU More Microgrid projects, many research activities are reported. They are ranging from the extended hierarchical controls, coordination between microgrids, power management, power quality control, fault analysis and protection scheme, energy trading, etc. Though not many researchers have worked on multiple microgrids reconfiguration, some of the works are captured in the following paragraph.

Considering the distributed generation concept for the generation unit in the microgrid, the high penetration of microgrids in the distribution system, and the most researchers design the reconfiguration in multiple microgrids by employing multi-agent system (MAS). The reconfigurations in multiple microgrids are presented [38,39], aiming to solve the problem of load supply and self-healing in a power network under failures of its element taken as the objectives. With MAS as the solution approach, different agents can be proposed by researchers. For example in [38], the agents are deterministic generation, stochastic generation, deterministic load, stochastic load, and energy storage systems and its microgrid system is modeled as two different layers, the power network layer and the MAS layer. The power network is implemented using MATPOWER, while the MAS layer, as many other research on MAS, is implemented using JADE. The simulation results of both researches [38,39] show a successful reconfiguration where the agents are capable to report the current available power, the priority loads, and the non-priority loads at a specific node.

2.5 SUMMARY

To conclude the discussion in this chapter, reconfiguration is one of important contingency plans since it is related with operational cost and reliability index. The reconfiguration in traditional power distribution, microgrid, and multiple microgrids may have the same objective and solution approaches; however, having microgrid in the power distribution system will increase the reliability index as the microgrid is able to connect or disconnect from the main grid and the RES inside is also able to connect or disconnect from the microgrid based on the necessity. Further, arranging neighboring microgrids in cluster will enhance system reliability even more because, in the event of unavailable support from the main grid, these neighboring microgrids can support each other by connecting or disconnecting the tie-lie switch between them. In addition, realizing that not many approaches have been used to solve multiple microgrids reconfiguration problem, this thesis proposes to contribute by conducting multiple microgrids reconfiguration using path search algorithm and PSO.

2.6 REFERENCES

[1] Q. Zhou, D. Shirmohammadi, and W.-H. Edwin Liu, “Distribution Feeder Reconfiguration for Operation Cost Reduction,” IEEE Trans. Power Sys., vol. 12, no. 2, pp. 730- 735. May, 1997.

[2] A.R. Berkeley III and M. Wallace, "A Framework for Establishing Critical Infrastructure Resilience Goals," National Infrastructure Advisory Council, Arlington, VA, Rep., 2010.

[3] E.D. Vugrin, et al., "A Mission Resilience Assessment Methodology for Infrastructure Disruptions," in IEEE Int. Camahan Conf. on Security Technology, Boston, MA, 2012, pp. 53-58.

[4] Battelle Energy Alliance, LLC. *Smart is Not Enough: Resilience and Securing the Power Grid* [Online]. Available: http://www.nist.gov/tip/wp/pswp/publicly-submitted-white-papers-energy.cfm

[5] K. Schneider and C.C. Liu. (2014, Jun 6). Smart Grid R&D Program Peer Review Meeting (2014) [Online]. Available: http://energy.gov/oe/downloads/2014-smart-grid-rd-peer-review-day-one-session-two.

[6] W.-C. Wu and M.-S. Tsai. “Application of Enhanced Integer Coded Particle Swarm Optimization for Distribution System Feeder Reconfiguration,” IEEE Trans. Power Syst., vol. 26, no. 3, pp. 1591-1599. Aug, 2011.

[7] D. Das. “A Fuzzy Multi-objective Approach for Network Reconfiguration of Distribution Systems,” IEEE Trans. Power Del., vol. 21, no. 1, pp. 202-209. Jan, 2006.

[8] M.-R. Andervazh, J. Olamaei, and M-. R. Haghifam. “Adaptive Multi-Objective Distribution Network Reconfiguration using Multi-Objective Discrete Particles Swarm Optimization Algorithm and Graph Theory,” IET Gen., Transm. & Dist., vol. 7, iss. 12, pp. 1367-1382. Dec, 2013.

[9] D.D. Popovic and R. M. Ciric., “A Multi-Objective Algorithm for Distribution Networks Restoration,” IEEE Trans. Power Del., vol. 14, no. 3, pp. 1134-1141. Jul, 1999.

[10] M.R. Narimani, et al., “Enhanced Gravitational Search Algorithm for Multi-Objective Distribution Feeder Reconfiguration Considering Reliability, Loss and Operational cost,” IET Gen., Transm. & Dist., vol. 8., iss. 1, pp. 55-69. Jan, 2014.

[11] A. Gonzales, et al., “A Sensitivities Computation Method for Reconfiguration of Radial Networks,” IEEE Trans. Power Sys., vol. 27, no. 3, pp. 1294-1301. Aug, 2012.

[12] W. Li, et al., “Reliability Evaluation of Complex Radial Distribution Systems Considering Restoration Sequence and Network Constraints,” IEEE Trans. Power Del., vol. 19, No.2, pp. 753-758. Apr, 2004.

[13] J. Li, et al., “Distribution System Restoration with Microgrids using Spanning Tree Search,” IEEE Trans. Power Sys., IEEE Trans. Power Sys., vol. 26, no. 6, pp. 3021-3028, Nov, 2014.

[14] G. Lambert-Torres, et al., “Particle Swarm Optimization Applied to System Restoration,” in IEEE Bucharest Power Technology Conference, Bucharest, Romania, 2009, pp. 1-6.

[15] M.W. Siti, et al., “Reconfiguration and Load Balancing in the LV and MV Distribution Networks for Optimal Performance,” IEEE Trans. Power Del., vol. 22, no. 4, pp. 2534-2540. Oct, 2007.

[16] X. Jin, et al., “Distribution Network Reconfiguration for Load Balancing Using Binary Particle Swarm Optimization,” in International Conference on Power System Technology, Singapore, 2004, pp. 507-510.

[17] H.P. Schmidt, et al., “Fast Reconfiguration of Distribution Systems Considering Loss Minimization,” IEEE Trans. Power Sys., vol. 20, no. 3, pp. 1311-1319. Aug, 2005

[18] L. Lu, et al., “An Improved Particle Swarm Optimization for Reconfiguration of Distribution Network,” in Fourth International Conference on Natural Computation, Jinan, China, 2008, pp. 453-457.

[19] W.-C. Wu and M.-S. Tsai, “Feeder Reconfiguration using Binary Coding Particle Swarm Optimization,” in International Journal of Control, Automation, and Systems, vol. 6, no. 4, 2008, pp. 488-494.

[20] C. Wang and Y. Zhang, “Distribution Network Reconfiguration Based on Modified Particle Swarm Optimization Algorithm,” in Proc. of The 5th International Conference on Machine Learning and Cybernetics, Dalian, China, 2006, pp. 2076-2080.

[21] B. Venkatesh, R. Ranjan, and H.B. Gooi, “Optimal Reconfiguration of Radial Distribution Systems to Maximize Loadability,” IEEE Trans. Power Sys., vol. 19, no.1, pp. 260-266. Feb, 2004.

[22] J. Torres-Jimenez, et al., “Reconfiguration of Power Distribution Systems using Genetic Algorithms and Spanning Trees,” in Electronics, Robotics and Automotive Mechanics Conference (CERMA), Cuernavaca, Mexico, 2010, pp. 779-784.

[23] F. Shariatzadeh, R. Zamora, and A.K. Srivastava, “Real Time Implementation of Microgrid Reconfiguration,” in North American Power Symposium (NAPS), Boston, MA, 2011, pp. 1-6.

[24] Y.D. Valle, et al., “Particle Swarm Optimization: Basic Concepts, Variants and Applications in Power Systems,” IEEE Trans. Evol. Comput., vol. 12, no. 2, pp. 171-195. Apr, 2008.

[25] F.V. Gomes, et al., “A New Heuristic Reconfiguration Algorithm for Large Distribution Systems,” IEEE Trans. Power Sys., vol. 20, no. 3, pp. 1373-1378. Aug, 2005.

[26] Nikos Hatziargyriou, Antonis Tsikalakis, et al, Microgrid Central Controller Strategies and Algorithms, MICROGRIDS Deliverable_DC1 Part 1, Contract No: ENK5-CT-2002-00610

[27] R.H. Lasseter, " Smart Distribution: Coupled Microgrids," Proc. of the IEEE, vol. 99, iss. 6, pp.1074-1082, May 2011.

[28] R.H. Lasseter, "CERTS Microgrid," in IEEE Int. Conf. on System of Systems Engineering, San Antonio, TX, 2007, p. 1-5.

[29] C. Ahn and H. Peng, "Decentralized Voltage Control to Minimize Distribution Power Loss of Microgrids," IEEE Trans. Smart Grid, vol. 4, no. 3, pp. 1297-1304, Sep, 2013.

[30] H. Lan, et al., "Modeling Analysis and Improvement of Power Loss in Microgrid," Hindawi Mathematical Problems in Engineering, vol. 2014, Sep, 2014. Available: http://www.hindawi.com/journals/mpe/raa/493560/

[31] A. Maknouninejad and Z. Qu, "Realizing Unified Microgrid Voltage Profile and Loss Minimization: A Cooperative Distributed Optimization and Control Approach," IEEE Trans. Smart Grid, vol. 5, no. 4, pp. 1621-1630, Jul, 2014.

[32] X. Wang and X. Li, "Fault Recovery of Micro-grid Based on Network Reconfiguration," in Asia-Pacific Power and Energy Engineering Conference (APPEEC), Shanghai, China, 2012, pp. 1-4.

[33] F. Shariatzadeh, et al., "Real-Time Implementation of Intelligent Reconfiguration Algorithm for Microgrid," IEEE Trans. Sustainable Energy, vol. 5, no. 2, pp. 598-607, Apr, 2014.

[34] Y. Qiao, Z. Lu, and S. Mei, "Microgrid Reconfiguration in Catastrophic Failure of Large Power Systems," in IEEE International Conference on Sustainable Power Generation and Supply (SUPERGEN), Nanjing, China, 2009, pp. 1-8.

[35] C. Shao, et al., "Operation of Microgrid Reconfiguration based on MAS (Multi-Agent System)," in IEEE Region 10 Conference(31194), Xi'an, China, 2013, pp. 1-4.

[36] S.A. Gopalan, et al., "Fault Analysis of an Islanded Multi-Microgrid," in IEEE Power and Energy Society General Meeting, San Diego, CA, 2012, pp. 1-6.

[37] N. Hatziargyriou, "Operation of Multi-Microgrids," in Microgrids: Architecture and Control, 1st ed. West Sussex, United Kingdom: WILEY, 2014, ch.5, sec. 5.1, p. 165.

[38] S. Rivera, A.M.Y. Farid, and K. Toumi, "Coordination and Control of Multiple microgrids Using Multi-Agent Systems," in Energypath 2013: Our Global Sustainable Energy Future. Philadelphia, PA, 2013, pp. 1-5.

[39] C.M. Colson, M.H. Nehrir, and R.W. Gunderson, "Distributed Multi-Agent Microgrids: A Decentralized Approach to Resilient Power System Self-healing," in IEEE 4th Int. Symp. on Resilient Control Systems, Boise, ID, 2011, pp. 83-88.

CHAPTER THREE: PROBLEM FORMULATION AND SOLUTION APPROACH FOR MULTIPLE MICROGRIDS RECONFIGURATION

3.1 INTRODUCTION

Understanding the current gap in the multiple microgrids power restoration research, a solution is proposed in this chapter, using graph theory. The chapter starts by elaborating the problem formulation in the form of objective functions as well as design requirement, equality constraints, and inequality constraints. Then, the proposed solution using graph theory is discussed. The microgrid network is represented as a graph $G(V,E)$. Using this graph, the outage area and the unsupplied load(s) are identified. The method proposed as the solution to restore the unsupplied load depends on the load priority type. The restoration approach for unsupplied priority loads is based on the path-searching algorithm using the Depth-First Search method, while the approach for unsupplied non-priority loads is based on the Adaptive Particle Swarm Optimization (APSO). A power flow calculation is used to verify that solution provided by both approaches. A detailed description for each solution approach is discussed below.

3.2 PROBLEM FORMULATION

3.2.1 Assumptions

Throughout this thesis, the followings assumptions will hold:

i) The Microgrid Model

Every single microgrid in this thesis is modeled as the modified CERTS microgrid. The modification is based on the assumption that each microgrid has only uncontrollable Distributed Energy Resources (DER), has non-priority loads in each feeder, and does not have any Energy Storage System (ESS).

ii) Type of Switches

Types of switches commonly used in power distribution system are the sectionalizing switch, the tie switch, and the recloser. A sectionalizing switch connects two buses in the same feeder of a microgrid and is normally in CLOSE position, while a tie switch connects two buses in two different feeders within the same microgrid or two different feeders on a different microgrid. The tie switch is normally in OPEN position. The recloser is a type of switch with ability to reclose several times in response to a temporary fault. If a permanent fault occurs, the recloser will open and close its contact until the maximum number of reclosing actions is reached. When this number is reached, the recloser will become permanently OPEN until it is manually reset. The sectionalizing and tie switch are types of switches used in this research. The recloser, on the other hand, is not used. The reason is that adding a recloser in the system will not change the algorithm. It will only change the time required to complete the algorithm.

iii) Timeline of Different Scenarios

Each scenario performed in this work generally follows the timeline presented in Table 3.1 below. The timeline is based on the simulation of a cluster of multiple microgrids consisting of two identical modified CERTS microgrids with both unsupplied priority and non-priority loads during an outage. As explained in part ii) above, changing a sectionalizing or a tie switch into a recloser will not have any impact to the algorithm; however, it will add more time to this timeline due to the reclosing action.

Table 3.1 Timeline of Different Scenarios

Sequence	Event Description	Duration (sec)
1	Protection System Action to detect Fault and open dedicated switches	0.0000
2	CB open	* 0.1500
3	Unsupplied loads identification based on outage location	2.3275
4	Priority Load Restoration using Patch Searching Algorithm	1.7287
5	Non-priority Load Restoration using Adaptive PSO Algorithm	10.6767
6	Verification using Power Flow	2.8708
	Total Duration	17.7537

* Based on Siemens Circuit Breaker, type: 3AK1 Technical Manual

3.2.2 Reconfiguration Objective Formulation

Reconfiguration Objective

The objectives of this reconfiguration problem are formulated as follows:

i) Maximizing the number of load supplied based on its priority when any disturbance occurred inside or outside the microgrid causing less power available to the loads

$$\max f_1(x) = \sum_{i=1}^{m} \left(\lambda_i y_i(x) P_{L,i}\right) \tag{1}$$

where

x : Line switch status

$f_1(x)$: Objective function to maximize number of energized load

m : Number of load bus

λ_i : Priority index in of load-i

$y_i(x)$: Status of load-i bus as a function of x

$P_{L,i}$: Power consumed by load-i (kW)

ii) Minimizing the number of switching to reconfigure the system

$$\min f_2(x) = \sum_{j=1}^{n} \left| x_j - x_j^f \right| \tag{2}$$

where

$f_2(x)$: Objective function to minimize the number of switching

n : Number of line switch

x_j : Switch-*j* status before reconfiguration

x_j^f : Switch-*j* status after reconfiguration

iii) Maximizing the usage of distributed generation unit, instead of exporting power from the main grid

$$\max f_3(x) = \sum_{k=1}^{p} \left(y_k(x)\, P_{g,k} \right) \tag{3}$$

where

x : Line switch status

p : Number of RES

$f_3(x)$: Objective function to maximize the number of DG to be used

$y_k(x)$: Status of bus-k as a function of x

$P_{g,k}$: Capacity of RES-*k* (*kVA*)

The Weighted-Sum Technique for Multi-Objective Problem Formulation

Since this thesis deals with the multi-objective problem, the main goal is no longer achieving the best-optimized value, but finding the best-compromised value for all objectives.

The weighted-sum technique, which also known as the "Scalarization" technique, is used to formulate the reconfiguration objectives addressed in this thesis as in (4) and (5). The advantages of the weighted-sum method lay on its simplicity and ease of implementation. The weight of each objective function is based on the relative importance of one objective function to another. In this thesis, maximizing the number of energized loads (objective function 1) is considered as the most important goal to be achieved; hence, the weight to this function is larger than the others.

$$F = w_1 . f_1 + w_2 . f_2 + w_3 . f_3 + w_4 . f_4 \tag{4}$$

$$w_1 + w_2 + w_3 + w_4 = 1 \tag{5}$$

where

w_1 : Relative weight for objective function f_1

f_1 : Objective function to maximize the load to be supplied

w_2 : Relative weight for objective function f_2

f_2 : Objective function to minimize switching

w_3 : Relative weight for objective function f_3

f_3 : Objective 3 maximize the use of Distributed Generation

w_4 : Relative weight for penalty function f_4

f_4 : Penalty function

3.2.3 Design Requirements and Constraints

Design Requirements

In order to achieve the objective of supplying power to the load based on its priority, two design requirements are considered.

i) Open-loop Topology

A power distribution system is commonly designed in a radial, open-loop, topology, where the protection relay only has an ability to cover one direction at a time. This is related with the fact that the conventional power distribution systems is usually fed only from one direction, which is from the centralized power plant to the load. This design is also related with the fact that upgrading the protection system to have an ability to look at two directions at a time will increase the operational cost. Based on the total switches involves in power distribution systems, the system usually can be connected in the loop topology; however, the power distribution system is still operated in the open-loop topology due to the protection relay setting and operational cost mentioned above. This open-loop topology is achieved by putting the tie switches in normally OPEN position.

As part of power distribution systems, the microgrid and the multiple microgrids adopt the same open-loop concept for its topology. However, the radial system, where power flows in single direction, can no longer be maintained. Accordingly, a protection relay needs to have the ability to look at two directions at a time. In contrary, there might be the case that the microgrid or DER is not available to power distribution systems, leaving the system with single power flow direction. This means, a relay has to be adaptive, where an option to operate in one or two directions is available at all times.

In this work, it is assumed that there are more load connected to the system than the available power from the main grid, causing a single power flow direction is maintained at all times. Further, it is also assumed that a microgrid or DER does not supply power back to the main grid. Hence, the open-loop topology has to be maintained continuously. The open-loop topology is preserved by the combination of loop detection method [1] and loop elimination methods [2]. If a loop is detected, one switch in that loop must be opened. The loop elimination method provides the algorithm to select the switch to be opened without causing any other node in the system to be islanded. Detail algorithms for the loop detection and loop elimination method will be elaborated in the next section.

ii) Load priority

Based on its importance, the load can be classified into several categories. The work presented in [3], shows three different load categories: 1) an ordinary load, which can be shed if necessary, 2) a controllable load under active demand supply management, and 3) a pivotal load, which demands an uninterrupted power supply. In this thesis, the load is classified only into two categories: the priority load and the non-priority load. The priority load is defined as the load, which in the case of an outage will endanger human life or human safety, meaning that without the presence of electricity some vital operations to support human lives does not exist. Examples of priority loads are hospitals and fire departments. Important facilities of the government service, such as airports, seaports, and police stations are also categorized as priority loads. In contrary, the non-priority load is defined as a load, which in the case of outage will cause economic losses, but not the loss of human life, human safety, and/or important government services. This type of load can be shed if necessary.

The load classification is identified by adding a "load priority index" into each load in the data file. In this thesis, there are two different load priority indexes being used regardless the number of load types: 1) the index used in Unsupplied Load Identification step and 2) the index used in objective function calculation in Non-priority Load Restoration Algorithm. The application of each load priority index is described as follows:

(a) Unsupplied Load Identification

The unsupplied load identification is a step in two-stage algorithm, which not only identifies how many loads are currently unreachable from any source due to a power outage, but also, classifies each load into the priority or non-priority category based on its importance. In the data file, a load with load priority index 1 is classified as the priority load category, while any other load with load priority index 2 is classified as the non-priority load category. If a system adopt more types of loads, for example, three types of loads as presented in [3], three different indexes, such as 1, 2, and 3 are used to identify the ordinary load, the controllable load, and the pivotal load respectively. The similar approach can be adapted for any other number of load types.

(b) Objective Function Calculation in Adaptive Particle Swarm Optimization

In order to make sure the objective function supplies the priority load first, another load priority index is incorporated into the calculation of the objective function 1. This load priority index is written as a λ in equation (1). The load priority index 500 is assigned to the priority load, while the index 50 is assigned to the non-priority load. These indexes are chosen to make sure that a maximum number of energized loads based on its priority will be the most important parameter to be achieved among any other objectives. Similar approach can also be adapted for any other number of load types. The larger the index represents the higher importance of a load, while the smaller index represents the less importance of a load.

Inequality Constraints

The optimization discussed in this thesis is limited by different operational and physical constraints. The following are the inequality constraints, which limited the reconfiguration goal:

i) Active Power of Generation

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad , i=1, ..., N_{Gen} \tag{6}$$

ii) Load Bus Voltage

$$V_{Li}^{min} \leq V_{Li} \leq V_{Li}^{max} \quad , i=1, ..., N_{Load} \tag{7}$$

iii) Line Capacity Limit

$$SL_{i}^{min} \leq SL_{i} \leq SL_{i}^{max} \quad , i=1, ..., N_{line} \tag{8}$$

where

P_G : Active Power Generation capacity in kW
P_G^{min} : Minimum Active Power generation capacity in kW
P_G^{max} : Maximum Active Power generation capacity in kW
V_L : Actual Bus Voltage in kV
V_L^{min} : Minimum Bus Voltage in kV
V_L^{max} : Maximum Bus Voltage in kV
SL : Line Limit in kW
SL^{min} : Minimum Line Limit in kW
SL^{max} : Maximum Line Limit in kW

Equality Constraints

In addition to the inequality constraints, the equality constraints also limit the search space of optimization solution. The equality constraints used in this thesis is the power flow calculation. The power flow calculation is not embedded into the optimization algorithm, but is performed separately. The power flow calculation has a purpose to verify if a potential solution of priority or non-priority load restoration step will lead the system into a safe and secure operations. The power flow simulation is based on the Three-phase Current Injection Method (TCIM) as presented in [4]. The TCIM power flow is chosen due to its ability to consider distribution system characteristics. Further, the TCIM power flow is also able to handle three-phase unbalanced system that is considered in this reconfiguration work.

3.3 SOLUTION APPROACH

3.3.1 Proposed Algorithm

The proposed algorithm to solve power restoration in multiple microgrids environment consists of two stages: the priority load restoration stage and the non-priority load restoration stage. The proposed algorithm is shown in the following Figure 3.1. When a fault happened in the system, the protection system isolates the faulted area. Then the unsupplied load(s) identification method searches for the load that is left without power. If there is no unsupplied load found, then the algorithm will stop and declare, "All Loads are Currently Supplied and Power Restoration is Not Needed". If there is any unsupplied load, the unsupplied load identification method will continue to identify which load is classified as the priority load type and which load is classified as the non-priority load type. The priority load type will be restored by the priority load restoration stage, which is based on the path-searching algorithm, while the non-priority load type will be restored by the non-priority load restoration stage, which is based on the adaptive particle swarm optimization (APSO). If there are unsupplied priority and non-priority loads, the restoration process is performed in two stages, started by the priority load restoration first, and followed by the non-priority load restoration.

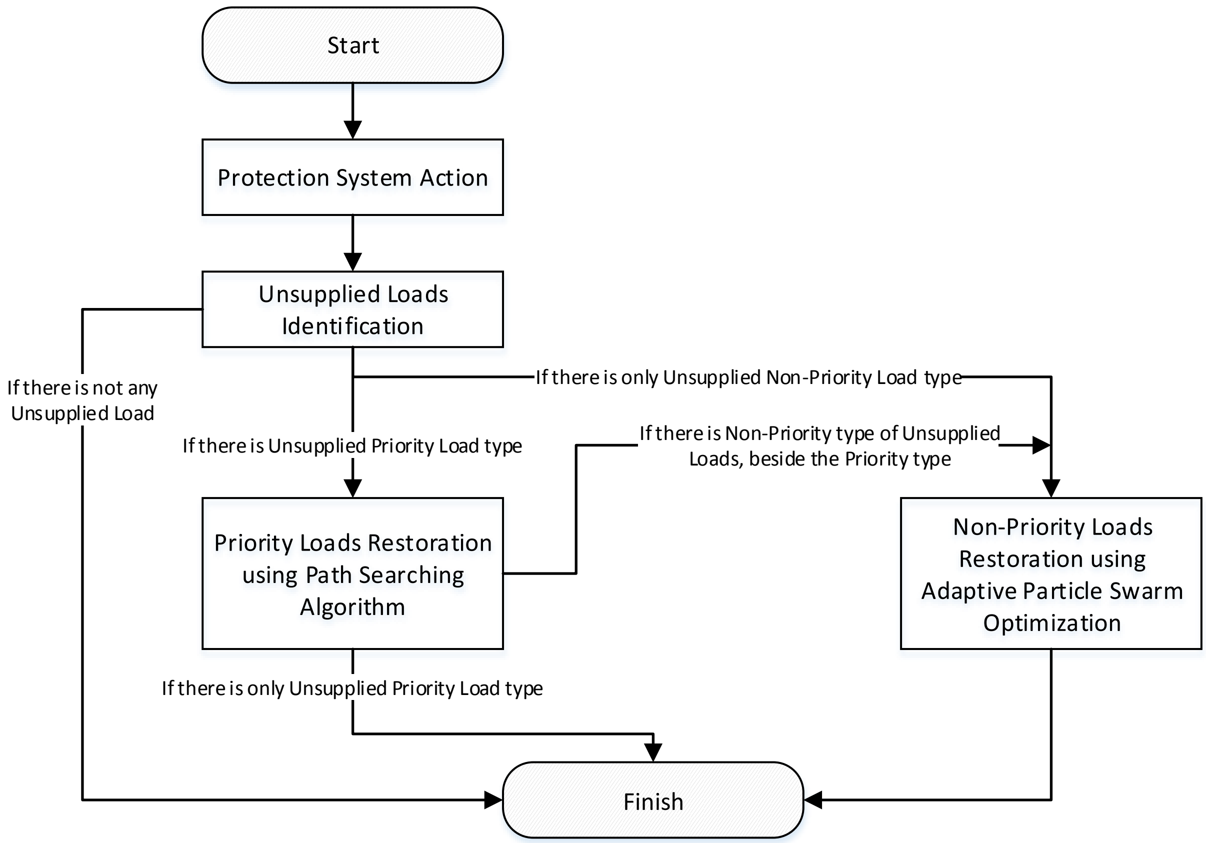
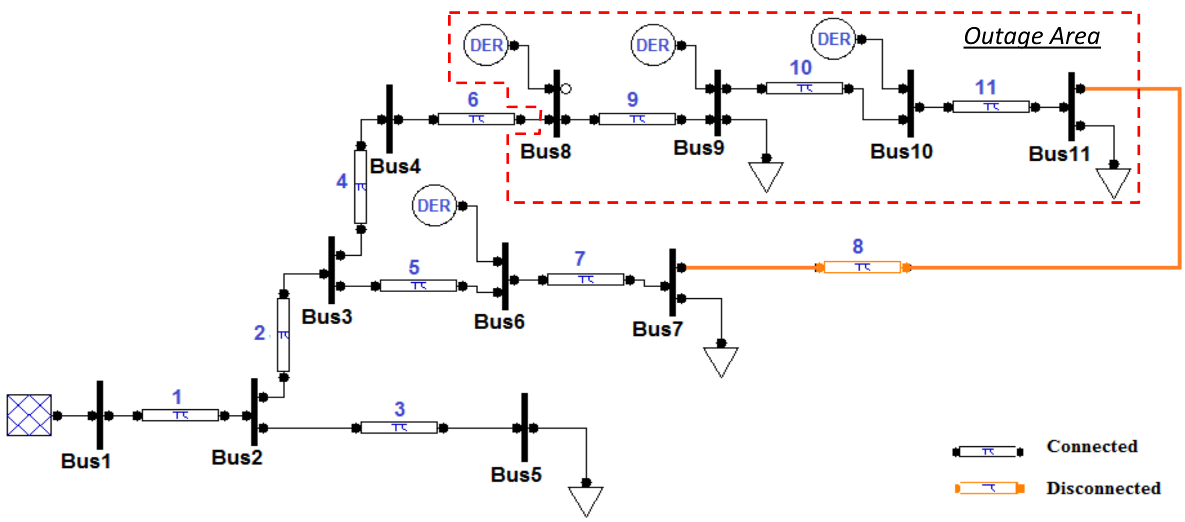


Figure 3.1 Two-Stage Power Restoration in Multiple microgrids Environment

3.3.2 Unsupplied Load(s) Identification Method

The unsupplied load(s) identification method works to identify which load is currently unsupplied due to an outage in the system. The unsupplied load(s) identification method works by calculating the distance between each load node to each source node using the shortest path algorithm [5]. However, instead of selecting the shortest path, any path returning "Inf" value is interpreted as the disconnection between two nodes. If no path is found between a load node to all source nodes, then the unsupplied load is identified. The example of unsupplied load identification in a single modified CERTS microgrid during a fault between bus 8 and 11 is described in the following Figure 3.2.




```
what is the beggining node of the edge?8

x =

     8

what is the end node of the edge?11

y =

    11


path_outage =

     8     9    10    11


edge_fault =

     8     9
     9    10
    10    11


all_path_faulted =

     0     1     2     3     2     3     4     4   Inf   Inf   Inf
     1     0     1     2     1     2     3     3   Inf   Inf   Inf
     2     1     0     1     2     1     2     2   Inf   Inf   Inf
     3     2     1     0     3     2     3     1   Inf   Inf   Inf
     2     1     2     3     0     3     4     4   Inf   Inf   Inf
     3     2     1     2     3     0     1     3   Inf   Inf   Inf
     4     3     2     3     4     1     0     4   Inf   Inf   Inf
     4     3     2     1     4     3     4     0   Inf   Inf   Inf
   Inf   Inf   Inf   Inf   Inf   Inf   Inf   Inf     0   Inf   Inf
   Inf   Inf   Inf   Inf   Inf   Inf   Inf   Inf   Inf     0   Inf
   Inf   Inf   Inf   Inf   Inf   Inf   Inf   Inf   Inf   Inf     0


unsupplied_loads =

     9    11
```

Figure 3.2 Example of Unsupplied Loads Identification

The unsupplied load(s) identification step is also responsible to map if the unsupplied load found belongs to the priority load or the non-priority load category. The identification is based on the load priority index as described in Section 3.2.3.

3.3.3 Unsupplied Priority Load Restoration Approach

Once the type of unsupplied load is identified, the unsupplied priority load will be restored using the path-searching algorithm. The algorithm of unsupplied priority load restoration is shown in the Figure 3.3. The unsupplied priority load restoration is initiated by closing all switches and searching for paths from an unsupplied node to reach each source node based on graph theory: the depth-first search (DFS) algorithm [6]. After all possible paths are searched; the reconfiguration algorithm is continued by eliminating those path(s) passing the faulted edges. The unsupplied priority load which has no path remaining is stored in the Islanded_list, while those which still have a remaining path will have its remaining path(s) after elimination to be stored in the Path_list matrix. If there is no path remains for all the unsupplied nodes, then the algorithm stops, and declares, "No Solution is Found". If there is at least one path, then the algorithm is moved to the next step. The next step of the restoration process is varied based on the unsupplied load path situation:

i) If only one path is found for only one unsupplied priority load, then this path become the potential solution.

ii) However, if there is more than one path is found for an unsupplied priority load, then the potential solution is chosen based on the minimum switching. The minimum switching is defined as the number of switch changing its latest status (during the fault) to be the opposite. For example, if the latest status is OPEN and the current switch status is CLOSE, then there is one

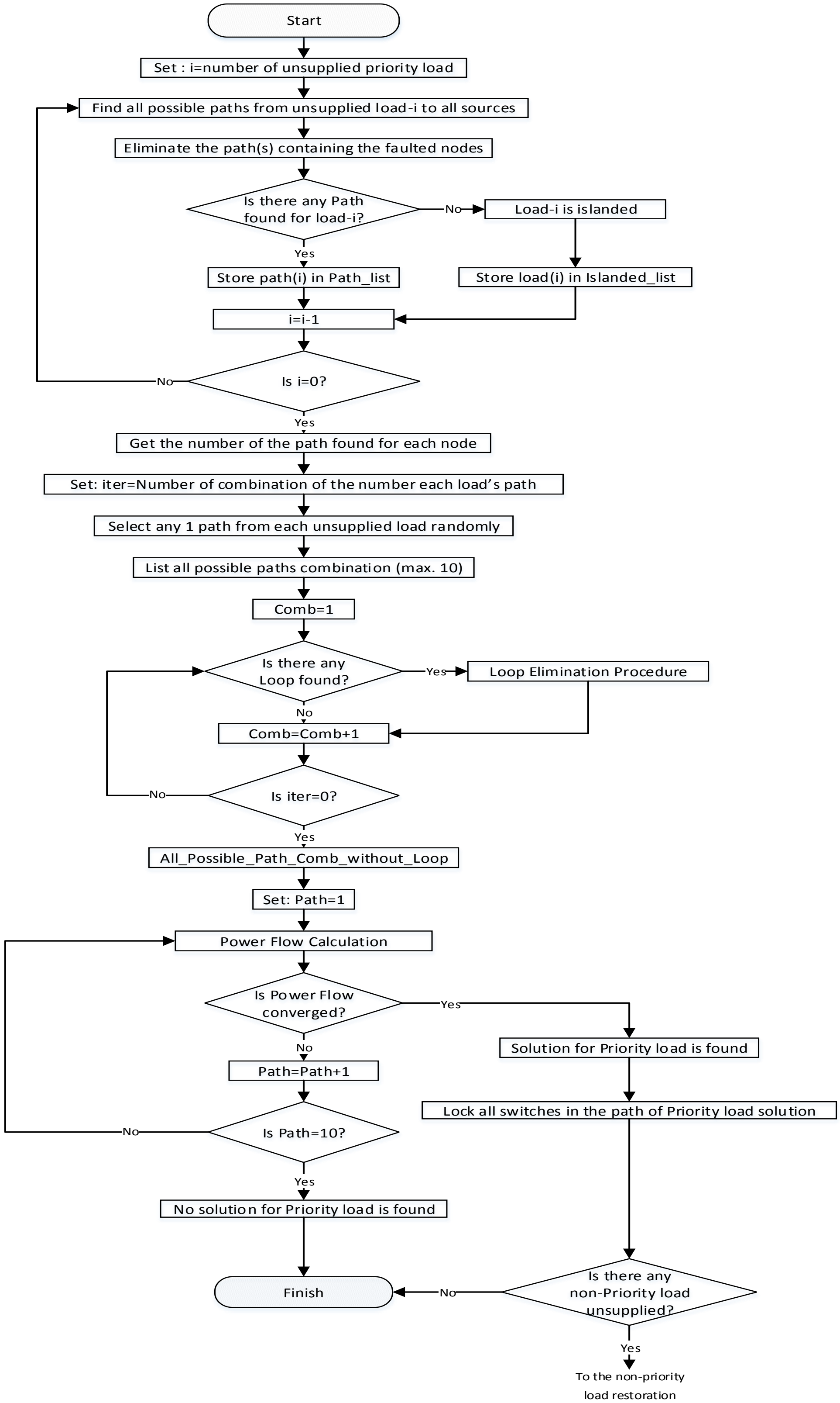


Figure 3.3 Unsupplied Priority Load Restoration Algorithm

switching happen. The same conclusion is applicable for a switch changing its status from CLOSE to OPEN. If the latest status of a switch is OPEN and it remains in the found path, then no switching happens. Similarly, for the switch with latest status is CLOSE and remains CLOSE in the found path, there is no switching for this particular switch.

iii) In the case that there is more than one unsupplied load and each of them has at least one path remaining, the potential solution is defined as the combination of each unsupplied load's path which will cause minimum switching in total.

After maximum 10 potential solutions are identified, the algorithm will check if each potential solution has the open-loop topology using Loop identification algorithm. If a loop is found in the potential solution, the loop elimination algorithm is executed to open any one switch in that loop that satisfies a set of rules, which will be explained later on. Once all potential solutions have open-loop topology, the algorithm is continued to check if there is any unsupplied non-priority load need to the recovered.

The power flow is calculated to find the potential solution that will lead the system in secure operations. The power flow calculation is started from the potential solution in the top to the bottom of the list. If the power flow is converged for a potential solution, the algorithm declares that the solution to recover the priority load is found, the solution is stored in the Restored_Priority_Load_Path, and the process is terminated. If the power flow is not converged, the algorithm will choose the next potential solution, and again calculate if the power flow is converged or not. If the power is still not converged, the algorithm will keep calculate the power flow for the next potential solution until the list is exhausted. If the list is exhausted and still no solution is found, then the algorithm stops, and declares, "There is No Solution". If an unsupplied non-priority load exists, the algorithm continues to the Non-Priority Load Restoration algorithm, with all switches in the Restored_Priority_Load_Path being locked.

Depth-First Search Method

As mentioned in the introduction of Section 3.3.4, all-possible paths from a load node to the entire source nodes are searched by using the basic method of the DFS algorithm. Refer to [7], DFS is an old searching algorithm in the graph theory aims to identify all nodes in a graph. The DFS algorithm prefers to identify the next level node of a current node rather than the other adjacent node in the same level. It will go deeper and deeper in the graph until it arrives in the last level node and no other next level node could be reached. After the last level node is reached, the DFS will perform backtracking to continue searching another node in a higher level that is previously left untouched.

Refer to Figure 3.4, the starting node is the node 1 in level 1. The algorithm will continue to node 2 in level 2. Instead of continue to node 7, which at the same level with node 2, the algorithm continue its search to node 3 in level 3, and node 4 in level 4. Once it reaches node 4 in level 4, the algorithm cannot go any further. Then, the algorithm continue to backtracking to node 3 and check if there is another node adjacent to node 3, but has not been visited before. Since node 5 is adjacent to 3 and has not been visited before, then the algorithm visit node 5. The algorithm then continue backtracking to node 2 in level 2, and visited node 6 that is adjacent to node 2, but has not been visited before. Since all nodes adjacent to node 2 have been visited, the algorithm continues backtracking to node 1 in level 1, to visit node 7, and then node 8 which have not been visited previously.

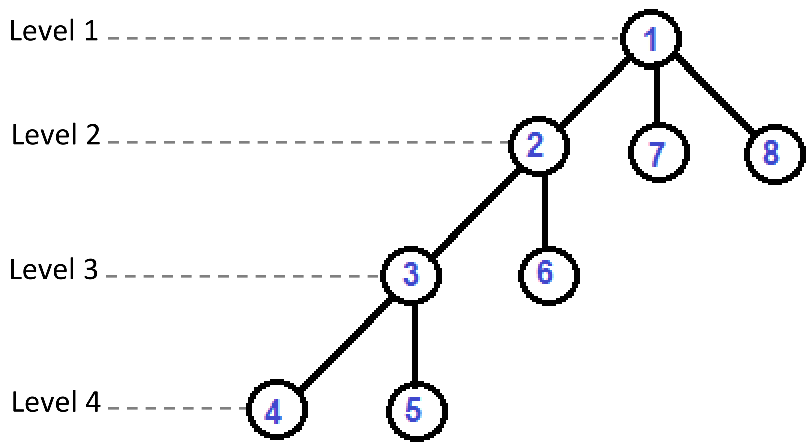


Figure 3.4 Depth-First Search Algorithm

This ability to search for node in the next level and record each node visited are the reasons why DFS is chosen as the method to restore priority load, instead of Breadth-First Search (BFS). This ability is considered will help each unsupplied load to find any source in efficient way.

In this thesis, the DFS works to find a source node from an unsupplied load node. Hence, the unsupplied node becomes the starting node, while each source nodes become the destination node whenever the DFS is run. When a source node is found, the path to this node is stored, and the algorithm is continued to find another source node. The algorithm stops searching when paths to all source nodes have been found. This means not all nodes must be visited; hence, searching time could be optimized.

Loop Identification Method

The loop identification method is based on the work by Joseph Kirk [1]. The algorithm is shown in Figure 3.5.

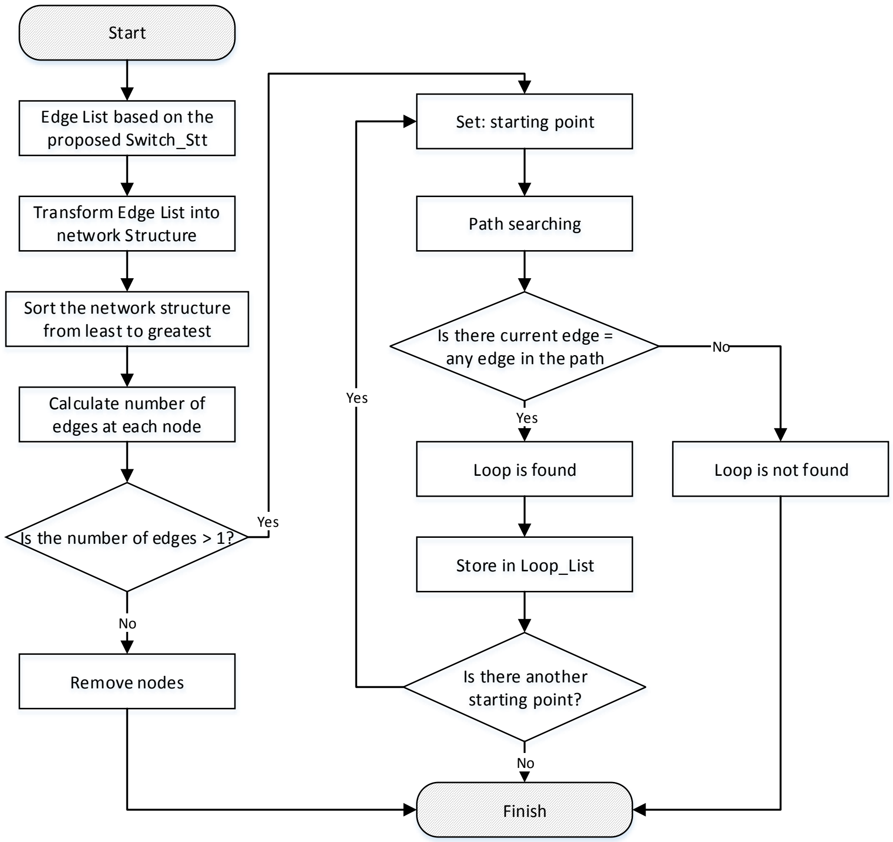


Figure 3.5 The Loop Detection Method

Loop Elimination Method

The loop elimination method is an algorithm to choose which switch should be opened in order to keep a graph in open-loop topology while at the same time preventing any other node become islanding as the impact of opening this switch. This loop elimination method is based on the modified input proposed in the APSO algorithm [2]. This loop elimination method adapts the fundamental loop vector from another work in [8] in order to prevent any islanding node at the exterior of a graph. In addition, two other vectors: common branch vector and prohibited group vector are introduced in [2] in order to prevent any islanding node in the interior of a graph. Further details about fundamental loop vector, common branch vector, and prohibited group vector are as follows:

(i) Fundamental Loop Vector

Based on [2], instead of listing all the loops exist in the graph, the fundamental loop vector only shows what is called "Fundamental Cycle". In graph theory, the fundamental cycle is defined as a loop which is formed by closing only one tie switch (normally open switch). The number of fundamental cycle of a graph can be calculated using the following equation as mentioned in [9]:

$$L = E - N + 1 \tag{9}$$

where:

L = Total Fundamental Cycle in a graph

E = Total edges in a graph

N = Total nodes in a graph

The number of switch to be opened is the same with the number of loops (fundamental cycle) found, which is the value of L in equation (9).

(ii) Common Branch Vector

The common branch vector is the list of the common branches of any two fundamental cycles.

(iii)Prohibited Group Vector

The prohibited group vector is the list of all combinations of two or more common branch vectors, where if at least one switch from each common branch vector is opened, one principal node will be islanded.

To avoid any node to be islanded, the following three rules are introduced in [2]:

(i) Each switch to be opened has to be a member of the concerned Fundamental Loop vector.

(ii) If there is more than 1 switch to be opened, only 1 switch belong to a common branch vectors can be opened.

(iii) If there is more than 1 switch to be opened, all switches may not belong to all common branch vectors forming a prohibited group vectors.

The potential switches to be opened have to satisfy all rules above. Otherwise, repair strategy should be performed to make sure all three rules are satisfied.

Power Flow Calculation

The power flow calculation is used to verify if a potential solution which will lead the microgrid system into a secure operations. The power flow calculation is applied starting from the top of potential solutions list. Once the power flow is converged for a solution, this potential solution becomes the solution of the Priority Load Restoration and the process stops; if the potential solutions lists are exhausted, yet no solution causing the power flow to converged, then no solution is found for the unsupplied priority load. The power flow calculation is using the three-phase current injection method (TCIM) as explained in Section 3.2.2.

3.3.4 Unsupplied Non-Priority Load Restoration Approach

If there is any Unsupplied Load identified as Non-Priority Load, the Adaptive Particle Swarm Optimization (APSO) is performed. The basic idea of APSO is to remove the infeasible individual during the initialization of swarm and to maintain open-loop topology. It works by transforming the swarm, which previously is the list of all switches' OPEN/CLOSE status, into the list of the switches to be OPEN. In other words, if the length of Swarm using original PSO is equal to the total switches in the system, using APSO, the length of Swarm is equal to the number of normally OPEN switches (tie switches). The number of tie switches is equal to the number of fundamental cycle in the system, as formulated in (9).

The following sub-section details the basic Particle Swarm Optimization (PSO), the previous reconfiguration work using PSO, specifically reconfiguration work in microgrid concept, the APSO, and the variables used in the non-priority load restoration algorithm.

Introduction to Particle Swarm Optimization

The Particle Swarm Optimization (PSO) is an optimization algorithm developed by Kennedy and Eberhart back in 1995. Similar with the other artificial intelligence optimization methods, this algorithm is developed by observing the nature phenomenon. PSO in particular is based on the study of the bird flocking system [10]. Initially the PSO was used to solve optimization problem in continuous time domain. However, as the optimization problems are also dealing with discrete time problem, Kennedy and Eberhart modified the algorithm to accommodate this need [11].

The PSO starts its search by generating a number of particles, called the swarms. These swarms move together in a group. The position and the velocity of each swarm is recorded and updated from time to time. This position of each particle is usually adjusted based on its own experience from time to time. The position of a particle evaluated at specific time, *t*, is compared to its own position in the previous time, *t-1*. This comparison chooses the best position of a particle, and it is named the personal best, *PBest*. Later this *PBest* is used as the memory of previous position by the next generation/evaluation, and so on. At each generation, the best particle among personal bests is also chosen. It is named the global best, *GBest*, and it will be used as the trajectory for the next generation. Each swarm moves with a specific velocity; this velocity is updated at each generation using the inertia weight factor. The inertia weight is a number with value less than one, but close to one so that the velocity is slightly decreased from time to time. Inertia weight is needed in PSO to avoid any swarm becoming uncontrollable [12].

Ever since PSO is developed, many researchers are using this method to solve the complex problem. Besides its fast convergence properties, PSO has fewer parameters compared to the other optimization technique, so the implementation is easier. In addition, PSO has a good memory capability and has ability to maintain the diversity of swarm [13].

Previous Reconfiguration Work using Particle Swarm Optimization

Using PSO to solve reconfiguration is considered a good option and very beneficial because of its fast convergence, but it usually does not explore all the search spaces to find the solution. In the case of fault in the power system causing some area left without power, the important parameter is the time required to isolate the fault and to re-energize the rest of the system [14]. This means searching through all the search spaces is not the goal of the load restoration. Hence, PSO is concluded a sufficient solution to solve the fault recovery in distribution system.

Different approaches have been applied with PSO to solve the power restoration problem. In [15], Discrete Particle Swarm Optimization (DPSO) and scale-free network concept were employed to perform power restoration strategy after a blackout. This approach uses network important degree and network reconfiguration efficiency as the input to the DPSO. The DPSO then provide suggestion of restoration target and relieve the reconfiguration burden. In [16], particle swarm optimization is used to restore power in shipboard power system. This approach is using Binary Particle Swarm Optimization (BPSO) in combination with graph theory. Graph theory is employed to map the zone with negative power balance and to find the path with positive power balance. In case there is no path with positive power balance, BPSO is run and decide which load to be shed. Different with [17], the PSO is applied by having two-stage of algorithms. The first algorithm is responsible to close normally open switches and to detect if there is any line overloaded. In case there is any line overloaded, the second algorithm is opening one of normally closed switches to remove the overloaded.

The Adaptive Particle Swarm Optimization Algorithm

The reconfiguration work in power system using the PSO associates the particle with the status of all switches in the system. This particle is produced randomly causing many infeasible individuals and violating the open-loop topology constraint. With one or two additional rules, many researchers transform an infeasible particle into feasible and radial individuals. Originally designed to achieve the objective of loss minimization in power system, the APSO modifies the PSO's particle to make sure, only feasible individuals are sent to the PSO algorithm. Further to the benefit of having all feasible individuals as the input, the APSO is chosen to be the solution approach in this thesis since the dimension of its particle, which equal to the number of fundamental loop, is considered much less than the original PSO; hence, less time is required to solve it. In this way, the feasibility of particle is improved and the open-loop topology is maintained. The algorithm of APSO is described inside the Non-Priority Load Restoration in Figure 3.6.

The method used in the APSO to modify the particle using the same method as loop detection and loop elimination technique described in Section 3.3.3. To maintain the open-loop topology, the elimination rules mentioned in the algorithm are important to avoid any node

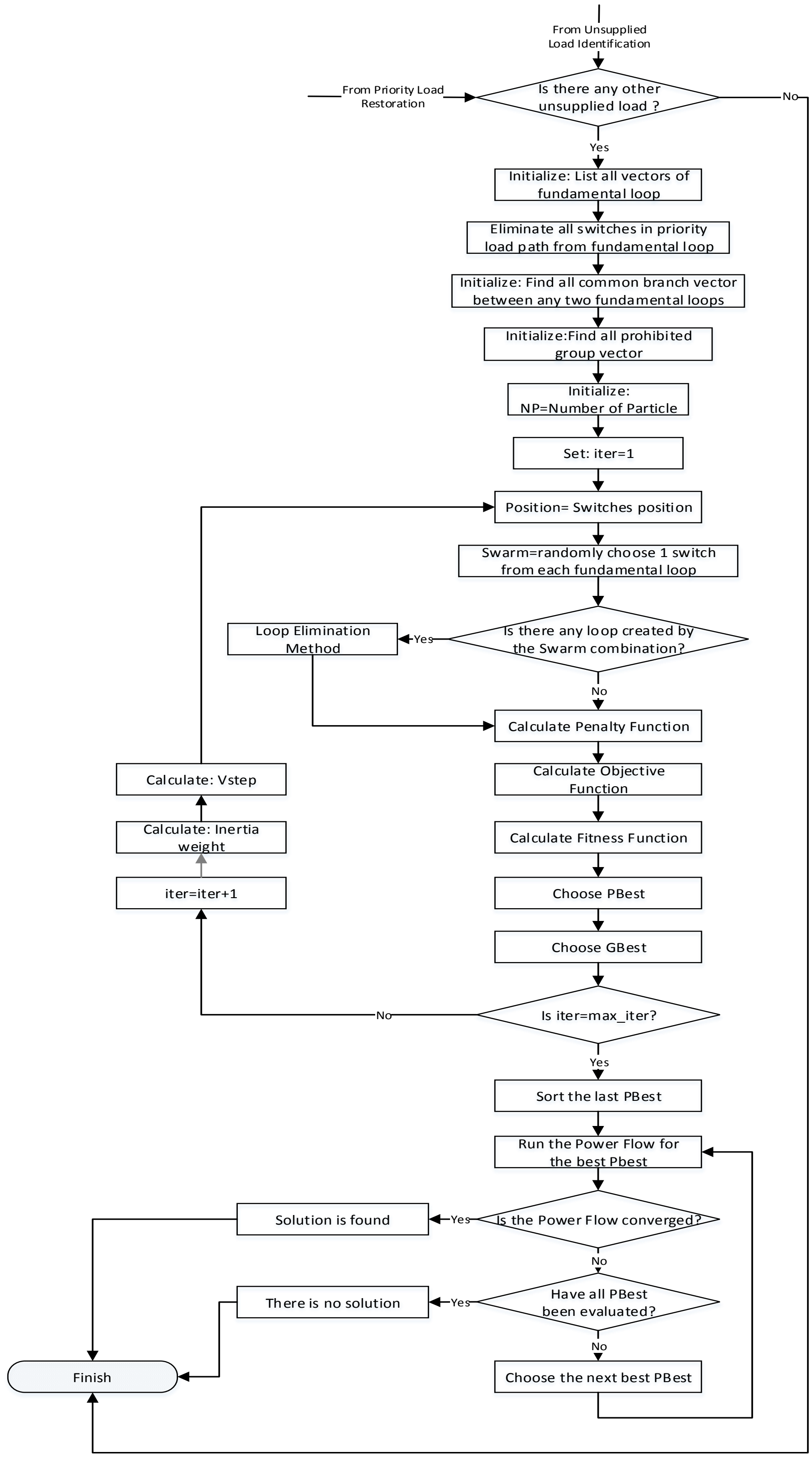


Figure 3.6 Unsupplied Non-Priority Load Restoration Algorithm

becomes islanded due to the incorrect selection of switch to be opened during particle formation. The elimination rules are as follow:

i) The number of switches formed a particle (the length of a particle) is equal to the number of the fundamental loop found

ii) If there is more than 1 switch to be opened, each member of the particle must come from the concerned fundamental loop vector; otherwise, this rule is violated

iii) If there is more than 1 switch to be opened, all members of a particle must may not come from all common branch vectors forming a prohibited group vectors; otherwise, this rule is violated. There must be one common branch vector does not have switch representative in the particle; otherwise, this rule is considered violated.

There are two differences between the loop elimination method in the APSO to the one in Priority Load Restoration Algorithm. First, the loop elimination method in the APSO eliminates all the switches or nodes previously found in the Priority Load Restoration algorithm from the fundamental loop vector. Second, whenever a rule is violated, the velocity of each violated individual in the APSO has to be updated using the following equation:

$$VStep = (-1) \times VStep \tag{10}$$

Variables used in APSO

Some variables used in APSO have different definition compare to the original PSO. The following are the definition of variables modified in APSO in order to meet the objectives:

i) *Position*: In APSO, the position is defined as a pointer to the particle in each fundamental cycle. The length of position vector is equal to the number of fundamental cycle under microgrid's fault condition

ii) *Particle*: The particle is the switch associated with the position of each fundamental cycle. This is the candidate switch to be opened to achieve the open-loop topology. The length of particle is equal to the length of fundamental cycle

iii) *Swarm*: The Swarm is a vector consists of 0 and 1 combination representing the CLOSE (1) and OPEN (0) status of all the switches in the Microgrid system. The value of individual switch inside Swarm is the status of switch configuration during the outage, but with updated values for several switches in the priority load path (change to be 1) and in the particle (change to be 0).

iv) *Penalty Function* : The penalty function is a function with the purpose to check if all constraints are satisfied. When a constraint is not satisfied, the penalty is applied. Since our goal is to maximize the fitness function and the penalty function contributes to the fitness function in the form of summation, each penalty will be charged a negative value. This means, violation to any constraint will lead to less value of fitness function.

v) *Fitness Function*: Fitness function is mathematically formulated as equation (4) in Section 3.2.2. The relative weight for each of objective function is considered based on the relative importance of each objective. In this thesis, the most important objective to be achieved is f_1, followed by f_4 and f_3, with the least important objective among the others is f_2. So, based on this level of importance, the weights assigned to each function are as follow:

$$w_1 = 0.4,\ \ w_2 = 0.1,\ \ w_3 = 0.2, w_4 = 0.3 \qquad (12)$$

Accordingly, the fitness function becomes:

$$F = 0.4\, f_1 + 0.1\, f_2 + 0.2\, f_3 + 0.3\, f_4 \qquad (13)$$

Verification using Three-Phase Current Injection Method Power Flow

Similar to the Priority Load Restoration Algorithm, after the APSO reaches the stop criteria and store the results in the list of potential solutions, the TCIM Power Flow is as validation criterion. The TCIM Power Flow is run for the top candidate first. If the TCIM Power Flow converged, the algorithm stops and solution is found. Otherwise, the algorithm will take the next top candidate and run it TCIM Power Flow. This procedure is continuously run until the TCIM Power Flow converges or until all potential solutions in the list have been evaluated, whichever comes first. If there is no candidate causing the power flow to be converged, then the algorithm stops, and declares, "No Solution is Found for the Unsupplied Non-Priority Load".

3.4 SUMMARY

The problem formulation and the solution approach have been elaborated out in this chapter. The problem formulated to achieve three objectives, they are to maximize the energized load during outage or abnormal situation based on load priority while keeping the number of switching minimized and the usage of DG maximized. The strategy used to address these problems has two-stage approach. The first stage is to restore the unsupplied priority load using the path-searching algorithm, which is based on the Depth-First search method, while the second stage is to restore the unsupplied non-priority load using the Adaptive Particle Swarm optimization (APSO). It is hoped that by using this two-stage algorithm not only the high priority loads are fully supplied, but also the restoration time of priority load are minimized. It is also important to emphasize that both algorithms work based on the graph theory approach.

3.5 REFERENCES

[1] Kirk, Joseph (2012). Loops in a Graph (http://www.mathworks.com/matlabcentral/fileexchange/10722), MATLAB Central File Exchange. Retrieved September 25, 2014.

[2] A. Swarnkar, N. Gupta, and K.R. Niazi, "Reconfiguration of Radial Distribution Systems with Fuzzy Multi-objective Approach using Adaptive Particle Swarm Optimization," in IEEE Power and Energy Society General Meeting, Minneapolis, MN, 2010, pp. 1-8.

[3] Y. Qiao, Z. Lu, and S. Mei, "Microgrid Reconfiguration in Catastrophic Failure of Large Power Systems," in IEEE International Conference on Sustainable Power Generation and Supply (SUPERGEN), Nanjing, China, 2009, pp. 1-8.

[4] P.A.N. Garcia, et al., "Three-Phase Power Flow Calculations Using the Current Injection Method," IEEE Trans. Power Sys., vol. 15, no. 2, pp. 508-514. May 2000.

[5] Kleder, Michael "All Pairs Shortest Path" Graph Solver (http://www.mathworks.com/matlabcentral/fileexchange/8808), MATLAB Central File Exchange. Retrieved August 28, 2014.

[6] J. Burkardt. ISC4221C-01. Class Lecture, Topic: "Graph Algorithms". Department of Scientific Computing, Florida State University, Tallahassee, FL, Aug 13, 2011.

[7] A. Brady. CS510. Class Lecture, Topic: “Depth-First Graph Traversal Algorithm”. Computer Science Program, Kalamazoo College, Kalamazoo, MI, May 4, 1997.

[8] J. Mendoza, et al., "Minimal Loss Reconfiguration using Genetic Algorithm with Restricted Population and Addressed Operators: Real Application," IEEE Trans. Power Sys., vol. 21, no. 2, pp. 948-954, May 2006.

[9] Glenn W. Stagg, Ahmed H. Ei-Abaid, *Computer Methods in Power Systems Analysis*, Mc-Graw Hill, 1968.

[10] J. Kennedy and R. Eberhart, "Particle Swarm Optimization," in IEEE Int. Conf. on Neural Network, Perth, WA, 1995, pp. 1943-1948.

[11] J. Kennedy and R.C. Eberhart, "A Discrete Binary Version of The Particle Swarm Algorithm," IEEE Int. Conf. on Systems, Man, and Cybernetics," Orlando, FL, 1997, pp. 4104-4108.

[12] J.C. Bansal, et al., "Inertia Weight Strategies in Particle Swarm Optimization," in IEEE 3rd World Congress on Nature and Biologically Inspired Computing, Salamanca, Spain, 2011, pp. 633-640.

[13] Y. del-Valle, et al., "Particle Swarm Optimization: Basic Concept Variants and Applications in Power Systems," IEEE Trans. Evol. Comput., vol. 12, no. 2, pp. 171-195, April 2008.

[14] J. Li. "Reconfiguration of Power Network based on Graph-theoretic Algorithms." Ph.D. Dissertation, Iowa State University, Ames, IA, 2010.

[15] Y. Liu and X. Gu, "Skeleton-Network Reconfiguration Based on Topological Characteristics of Scale-Free Networks and Discrete Particle Swarm Optimization," IEEE Trans. Power Sys. vol. 22, no. 3, pp. 1267-1274, August 2007.

[16] N. Kumar, A.K. Srivastava, and N.N. Schulz, "Shipboard Power System Restoration Using Binary Particle Swarm Optimization," in IEEE North America Power Symp., Las Cruces, NM, 2007, pp. 164-169.

[17] G. Lambert-Torres, et al., "Particle Swarm Optimization Applied to System Restoration," in IEEE Power Tech. Conf., Bucharest, Romania, 2009, pp. 1-6.

CHAPTER FOUR: SIMULATION RESULTS FOR MULTIPLE MICROGRIDS RECONFIGURATION

4.1 INTRODUCTION

In this chapter, several cases are simulated using the two-stage method explained in Chapter 3. The purpose of this chapter is to demonstrate that the proposed method is able to perform reconfiguration required by the multiple microgrids to restore power to the loads as well as improve grid resiliency. The chapter starts by describing several assumptions for simulation cases, explaining each simulation case performed, reporting simulation results, and discussing as well as analyzing the results in comparison to criteria of a self-healing system. The chapter ends by summarizing the works performed in this chapter as well as simulation results and the analysis.

4.2 ASSUMPTIONS FOR SIMULATION

All assumptions made in Chapter 2 and 3 as well as additional assumptions to make the case studies more intricate are presented herewith:

i) The multiple microgrids used in this thesis is based on CERTS concept as discussed in Section 2.3.3. Hence, each microgrid hold the following assumptions as explained in Section 2.3.2: 1) the modification does not change either the way microgrid operates or the simulation results, 2) the substation transformer between main grid and the microgrid are removed, 3) the isolation transformer at Zone-5 is removed, 4) Zone-3 and Zone-4 are supplied by a three-wired cable, and 5) the loads in Zone-6 is included in the Static Switch protection zone.

ii) The microgrid used for simulation case operates in low voltage.

iii) The total power generated by DER for each microgrid is considered different from one case to another. In addition, the control for number of generation is attached into each DER (RES/DG). RES is the only type of generation unit could be maximized in this work since DG will only be maximized during emergency.

iv) Utilizing DER as a power supply is preferred than the main grid for loss minimization.

v) Total power consumed by load is generally the same, except for some cases of note.

vi) The multiple microgrids model used in this thesis is not equipped with ESS.

vii) The multiple microgrids model used in this thesis is not equipped with automatic under voltage/under frequency load shedding.

4.3 SIMULATION CASES

Several cases are simulated in this work, including the base case and operation with contingencies. Detailed descriptions for each case are as follow:

Base Case

The multiple microgrids system explained in Section 2.3.3 is used as the base for this simulation. The base case shows the microgrid is operating in normal condition, when all loads are supplied, all DER units are generating their nominal power, all distribution lines are within the line-loading limit, and no contingency or abnormality occurs in the system. The DER parameters and load parameters for the simulation are presented in Table 4.1 and 4.2 respectively.

The base case, as well as any other case, involves 21 buses and 23 lines. Each line is equipped with one switch. As each switch is dedicated to a line, the number attached to each switch represents the number of the line where the switch belongs. In this case, all sectionalizing switches are in the closed position, while all tie switches are in the opened position. Table 4.3 provides line parameters as well as displays the switch reconfiguration during normal operations in column "Switch Status".

Table 4.1 DER Parameters for Base Case

Bus No.	Type	Nominal Capacity (kVA)	Microgrid #
6	DER-I	70.7017	1
8	DER-II	70.7017	
9	DER-III	49.4975	
10	DER-IV	70.7017	
16	DER-I	70.7017	2
18	DER-II	70.7017	
19	DER-III	49.4975	
20	DER-IV	70.7017	

Table 4.2 Load Parameters for Base Case

Bus No.	Type	Capacity		Microgrid #
		P_L (kW)	Q_L ($kVAR$)	
5	Non-Priority	48.8000	36.6000	1
7	Priority	84.8528	63.6396	
9	Priority	77.3103	57.9827	
11	Non-Priority	79.9502	59.9627	
15	Non-Priority	46.6666	34.5000	2
17	Priority	52.5680	39.4260	
19	Priority	81.0816	60.8112	
21	Non-Priority	69.8358	52.3769	

Table 4.3 Line Parameters for Base Case

From Bus	To Bus	Line No.	Switch Status *)	Line Impedance	
				R(Ω)	***X(Ω)***
1	2	1	1	0.045	0.186
1	12	2	1	0.045	0.186
2	3	3	1	0.023	0.093
2	5	4	1	0.090	0.370
3	4	5	1	0.023	0.093
3	6	6	1	0.023	0.093
4	8	7	1	0.023	0.093
6	7	8	1	0.023	0.093
7	11	9	0	0.045	0.186
8	9	10	1	0.023	0.093
9	10	11	1	0.023	0.093
10	11	12	1	0.023	0.093
11	21	13	0	0.045	0.186
12	13	14	1	0.023	0.093
12	15	15	1	0.090	0.370
13	14	16	1	0.023	0.093
13	16	17	1	0.023	0.093
14	18	18	1	0.023	0.093
16	17	19	1	0.023	0.093
17	21	20	0	0.045	0.186
18	19	21	1	0.023	0.093
19	20	22	1	0.023	0.093
20	21	23	1	0.023	0.093

*) *Switch with status 1 is a normally closed switch, named sectionalizing switch. Switch with status 0 is a normally opened switch, named tie switch*

Operation with Contingencies

The performance of the proposed algorithm and the impact of having multiple microgrids will be evaluated under different contingencies. The following descriptions explain every simulation to be conducted.

a. One microgrid is islanded after fault

In this case, it is assumed that a fault happened at an outgoing feeder of the main grid to a microgrid. As the protection systems isolate the fault, the microgrid changes its operation mode to islanding. Let us assume that the fault occurred at the feeder to MG-2, and now MG-2 is islanding. Before the fault occurred, MG-2 was generating power using its own DERs unit with ability to cover 80% of the load, while the other 20% were purchased from the main grid. This means when this fault occurred, DERs are not able to supply all the loads; the under frequency load shedding protection is assumed to be activated causing the load at Bus-21 to be shed. It is important to note that the load at Bus-21 is the non-priority type. The current switch status related with this case is presented in Table 4.4.

Table 4.4 Initial Switch Status for each Case Study

Simulation Case	Switch in CLOSE Position	Switch in OPEN Position
One microgrid is islanding	1, 3, 4, 5, 6, 7, 8, 10, 11, 12, 14, 15, 16, 17, 18, 19, 21, 22	2, 9, 13, 20,23
Outage at a feeder inside a microgrid	1, 2, 3, 4, 5, 6, 8, 14, 15, 16, 17, 18, 19, 21, 22, 23	7, 9, 10, 11, 12, 13, 20
A fault within a microgrid when two microgrids are islanded	3, 4, 5, 6, 7, 8, 10, 11, 12, 14, 15, 16, 17, 18, 19, 21, 22, 23	1, 2, 11, 18, 16, 17, 27

The simulation is performed to demonstrate the ability of the developed two-stage method to identify the type of unsupplied load and to provide a solution to the load based on its type. Since the load is the non-priority type, the problem is expected to be solved using the Non-Priority Load Restoration Algorithm. The results will report which switch to be turned on or off in order to accomplish the objectives of maximizing the number of supplied loads, minimizing the number of switching, and maximizing the utility of DERs while satisfying all the operating constraints.

b. A fault within a microgrid leading to load loss

In this case, one of the feeders in MG-1 is assumed to be out of service due to a fault. This causes switch No. 7 to be open. Let us also assume that the fault happens due to a storm hitting several areas, such that the lines between Bus-7 to Bus-10, line 10, 11, and 12, are out of service. The DER at Bus-9 is assumed out of service and the loads at Bus-9 and Bus-11 are accordingly losing their power supply. Both loads at Bus-9 and Bus-11 are the priority load types. The summary of switch status related with this case is presented in Table 4.4. The following Table 4.5 the modification on the type of load used only for this case study.

Table 4.5 Load Parameters for Case 2

Bus No.	**Type**	**Capacity**		**Microgrid #**
		P_L (*kW*)	Q_L (*kVAR*)	
5	Non-Priority	48.8000	36.6000	1
7	Priority	84.8528	63.6396	
9	Priority	77.3103	57.9827	
11	Priority	79.9502	59.9627	
15	Non-Priority	46.6666	34.5000	2
17	Priority	52.5680	39.4260	
19	Priority	81.0816	60.8112	
21	Non-Priority	69.8358	52.3769	

When the purpose of the previous case study is to show the ability of the developed algorithm to restore unsupplied non-priority loads, the purpose of this simulation is to show whether the developed algorithm is able to identify priority loads and to overcome the outage using the Priority Load Restoration Algorithm. In addition, we would like to show whether the algorithm could identify if there is a load that cannot be restored because no path is found between that load to all sources.

c. A fault within a microgrid when two microgrids are islanded

For this particular case, a slight modification is made into the multiple microgrids model. The modification is the addition of switch attached to the loads, which allows us to have different type of loads connected to the same bus (e.g., priority load at Bus-15 and non-priority load 16 at Bus-14). This multiple microgrids cluster with load switch is presented in Figure 4.1.

In this case, microgrids MG-1 and MG-2 are in islanded mode, but each microgrid is able to support its loads. When a fault happened on DER at Bus-13, line 14 and 15 are opened to

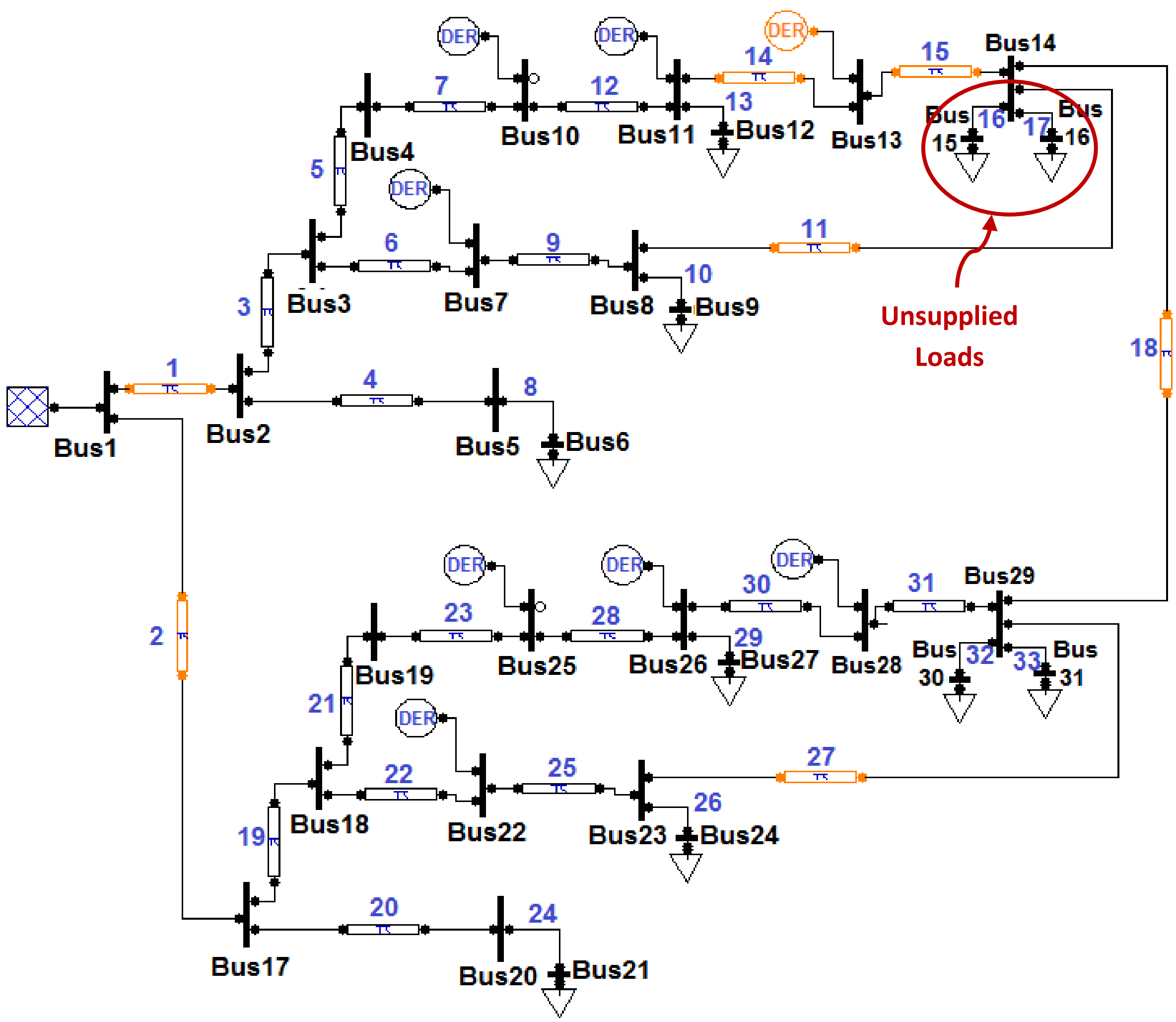


Figure 4.1 Multiple microgrids with Load Switch for Case Study 3

isolate the fault. This situation causes microgrid MG-1 to lose most of its power generation; hence, the loads at Bus-15, a priority load, and Bus-16, a non-priority load, are left without power. Microgrid MG-2, on the other hand, has enough power to its load and operating in normal operations. The DER, load, and line parameters for this study are shown in Table 4.6, 4.7, and 4.8.

The purpose of this study is to show the ability of the developed algorithm to restore the load based on its priority, especially when there is only limited power available at the neighboring microgrid. The simulation aims to find the solution for the following question: Which load will be restored by the developed algorithm in the case of limited available power?

Table 4.6 DER Parameters for Case 3

Bus No.	Type	Nominal Capacity (kVA)	Microgrid #
9	DER-I	125	1
10	DER-II	125	
12	DER-III	0	
21	DER-I	115	2
24	DER-II	125	
25	DER-III	125	
27	DER-IV	125	

Table 4.7 Load Parameters for Case 3

Bus No.	Type	Capacity		Microgrid #
		P_L (kW)	Q_L ($kVAR$)	
6	Non-Priority	48.8000	36.6000	1
8	Priority	84.8528	63.6396	
11	Priority	77.3103	57.9827	
14	Priority	48.0000	36.0000	
15	Non-Priority	48.0000	36.0000	
20	Non-Priority	46.6400	34.9800	2
23	Priority	52.5680	39.4260	
26	Priority	81.0816	60.8112	
29	Priority	48.0000	36.0000	
30	Non-priority	48.0000	36.0000	

Table 4.8 Line Parameters for Case 3

From Bus	To Bus	Line No.	Switch Status *)	Line Impedance	
				R(Ω)	***X(Ω)***
1	2	1	0	0.045	0.186
1	17	2	0	0.045	0.186
2	3	3	1	0.023	0.093
2	5	4	1	0.090	0.370
3	4	5	1	0.023	0.093
3	7	6	1	0.023	0.093
4	10	7	1	0.023	0.093
5	6	8	1	0.023	0.093
7	8	9	1	0.023	0.093
8	9	10	1	0.023	0.093
8	14	11	0	0.045	0.186
10	11	12	1	0.023	0.093
11	12	13	1	0.023	0.093
11	13	14	0	0.023	0.093
13	14	15	0	0.023	0.093
14	15	16	0	0.023	0.093
14	16	17	0	0.023	0.093
14	29	18	0	0.045	0.186
17	18	19	1	0.023	0.093
17	20	20	1	0.090	0.370
18	19	21	1	0.023	0.093
18	22	22	1	0.023	0.093
19	25	23	1	0.023	0.093
20	21	24	1	0.023	0.093
22	23	25	1	0.023	0.093
23	24	26	1	0.023	0.093
23	29	27	0	0.045	0.186
25	26	28	1	0.023	0.093
26	27	29	1	0.023	0.093
26	28	30	1	0.023	0.093
28	29	31	1	0.023	0.093
29	30	32	1	0.023	0.093
30	31	33	1	0.023	0.093

*) *Switch with status 1 is a normally closed switch, named sectionalizing switch.*

Switch with status 0 is a normally opened switch, named tie switch

4.4 SIMULATION RESULTS

The results of all cases are presented in the following Table 4.9. The "unsupplied loads" column shows the number of priority and non-priority load bus left without power during the simulation. The "final reconfiguration column" is the list of opened and closed switches suggested by the developed algorithm to solve the problem. The "number of switching" column is the comparison of switch status after the reconfiguration, except for the faulted switches, to the switch status before the reconfiguration. Each changed status counts as one switching. Otherwise, no switching occurs. Finally, the "restored load" column indicates the load bus receiving power after the final reconfiguration, while the "non-restored load" column indicated the load bus remains without power even after the final reconfiguration.

4.5 DISCUSSION/ANALYSIS OF THE SIMULATION RESULTS

Referring to [1], to be an effective self-healing system, a microgrid 1) has to be able to interpret emergencies, 2) has to react promptly to an abnormal situation, and 3) has a decision-making framework that guides the system to safe operations. These criteria allow the improvement of power grid resiliency, especially through the ability of fast recovery. Hence, the main discussion on the following sub-sections will be based on the above-mentioned criteria of an effective self-healing system. The following question will be considered: Has the criteria been achieved? If yes, is there anything left to be improved? If not, what is the reason and how is to improve? The discussion will also look at the ability of the developed algorithm to recognize security priority, in this case is in the form of load priority.

Table 4.9. Simulation Results

Simulation Case	Unsupplied Loads		Final Reconfiguration (Switch Number)	No. of Switching	Restored Load (Bus No.)	Non-restored Load (Bus No.)
	Priority (Bus No.)	Non-Priority (Bus No.)				
Base Case	-	-	*Closed Switch*: 1,2,3,4,5,6,7,8,10, 11,12,14,15,16,17, 18,19,21,22,23 *Opened Switch*: 9,13,20	-	-	-
One microgrid is islanded after the fault	-	21	*Closed Switch*: 1,3,4,5,6,7,8,9,10, 11,13,14,15,16,17, 18,19,20,21,22 *Opened Switch*: 2,12,23	4	21	-
A fault within a microgrid leading to load loss	9, 11	-	*Closed Switch*: 1,2,3,4,5,6,8,9,14, 15,16,17,18,19,21, 22,23 *Opened Switch*: 7,10,11,12,13,20	1	11	9
Another case of fault within a microgrid	15	16	*Closed Switch*: 3,4,5,6,7,8,9,10,12, 13,16,18,19,20,21, 22,23,24,25,26,28, 29,30,31,32,33 *Opened Switch*: 1,2,11,14,15,27	2	15	16

a. One microgrid is islanded

After the fault occurred, MG-2 has to operate in islanding mode. This condition causes MG-2 to lose 20% of its power supply. As the impact, a non-priority load at Bus-21 is shed by the protection.

The reconfiguration action taken to solve the problem in this case is presented in Table 4.9. The final reconfiguration for this case is having switches 1,3,4,5,6,7,8,9,10,11,13,14,15, 16,17,18,19,20,21,22 in closed position, while switches 2,12,and 23 are in opened position. This configuration is shown in the following Figure 4.2.

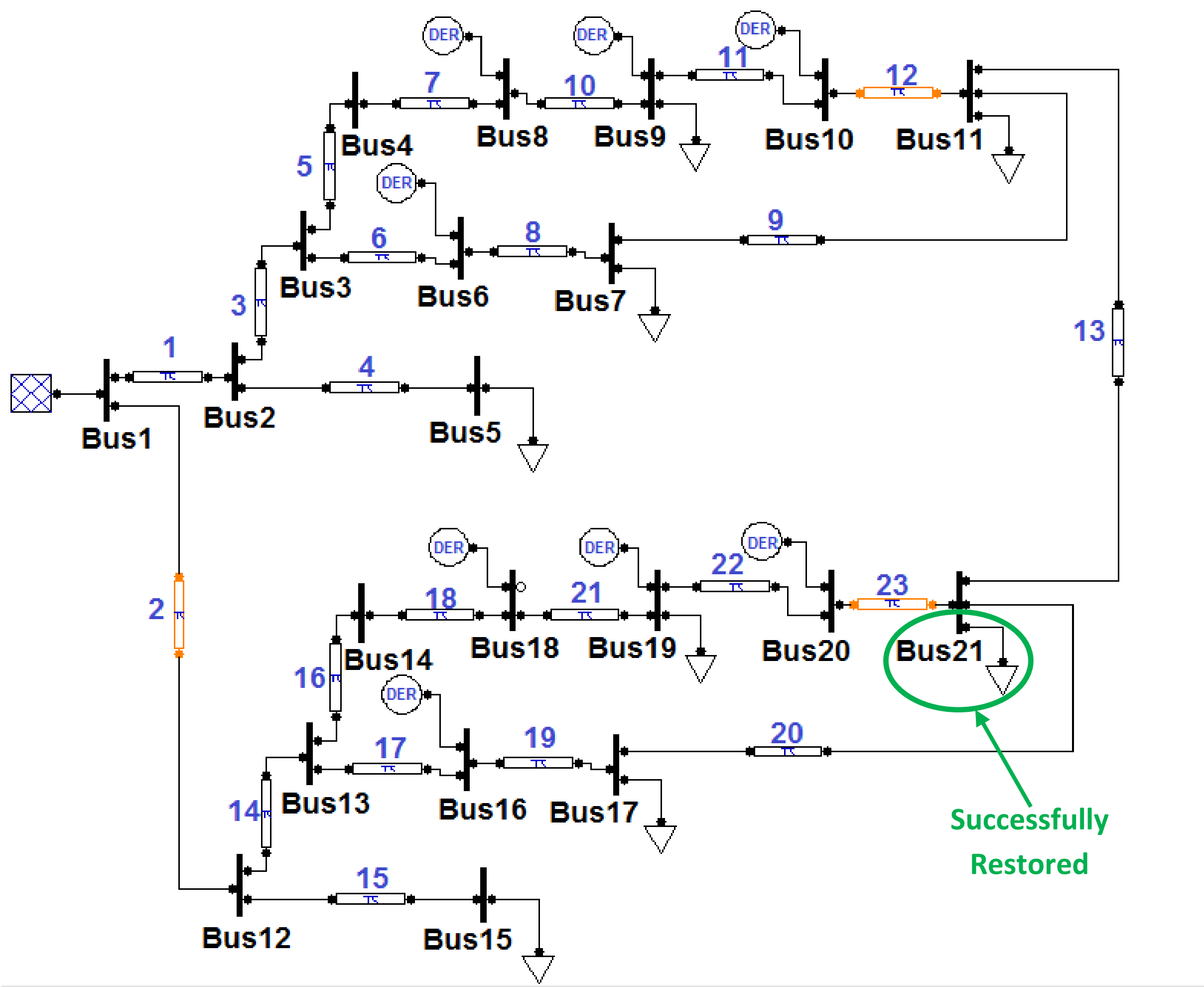


Figure 4.2 Solution of Case Study1

The developed two-stage reconfiguration algorithm has successfully brought the load at Bus-21 back into operation. As there were only one unsupplied load in this case study, and the proposed algorithm has successfully restored this load; hence, all loads (100%) are currently supplied. The load at Bus-21 is restored by closing switch number 9, 13, and 20, and opening switch number 12. The opening of the switch number 12 located at MG-1 helps with maintaining open-loop topology. At this final configuration, all DERs are also currently in operations. Further, as this final configuration has been verified by having a converged power flow; hence, this configuration is the sufficient solution to this case study.

With the load at Bus-21 being supplied, not only this simulation has successfully demonstrated the ability of the developed algorithm to interpret the emergency and react promptly to restore load at Bus-21 as required by the self-healing criteria, but also the advantages of having multiple microgrids as a cluster for improving grid resiliency. Microgrid MG-1 in this case provides support to the community loads by closing switch no. 13 connecting to microgrid MG-2. Without the concept of multiple microgrids, the load at Bus-21 will be left unsupplied until the fault on the main grid side is successfully removed because microgrid MG-2 has no ability to connect to the main grid due to the fault.

One interesting question to be discussed related with the results is "Is it optimum to have four switching actions only to restore 1 load?" The four switching actions are needed to ensure the cluster is connected as one graph that is required by the algorithm developed. When the fault occurred and the protection shed the load, there were 3 separated graphs representing this system. If each graph is considered as a node, by logic, we can easily examine that only 2 lines are needed to combine the 3 graphs into 1 graph.

Here, based on the design of the multiple microgrids cluster and the developed algorithm, the author would like to explain the presented solution is considered optimum. First, this problem is formulated as a multi-objective problem; hence, the solution is not the optimum solution for an objective function, but rather a compromised solution to all the objective functions as well as the penalty function to achieve the maximum value of fitness function. Second, as the formulated problem is a multi-objective problem, the output of the non-priority load restoration based on APSO is not as any other output of particle swarm optimization, which is the global best, but all the personal best of each particle. These lists of potential solutions are then sorted based on the largest fitness function. However, the one in the top of the list is not accordingly become the solution to this problem. Power flow calculation is used as the final verification of the potential solution. As can be seen in the following Figure 4.3, the current solution is not in the top of the sorted potential solutions, but indeed is the first solution resulting in a converged power flow.

All_Personal_Best_Switch =

Columns 1 through 11 Columns 12 through 22

1	3	4	5	6	7	8	0	10	11	12	13	14	15	16	17	18	19	20	21	22	0
1	3	4	5	6	7	8	0	10	11	12	13	14	15	16	17	18	19	20	21	22	0
1	3	4	5	6	7	8	0	10	11	12	13	14	15	16	17	18	19	20	21	22	0
1	3	4	5	0	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	0
1	3	4	5	6	0	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	0
1	3	4	5	6	7	8	9	10	0	12	13	14	15	16	17	18	19	20	21	22	0
1	3	4	5	6	7	8	9	10	11	0	13	14	15	16	17	18	19	20	21	22	0
1	3	4	5	6	0	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	0
1	3	4	0	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	0
1	3	4	5	6	7	8	9	10	11	0	13	14	15	16	17	18	19	20	21	22	0

Figure 4.3 All Potential Solutions for Case Study 1

Related with several potential solutions causing non-convergence power as shown in Figure 4.3, there are several possible causes as discussed in [2], such as: 1) there is not enough reactive power available for the load and losses in some part of the system, and 2) the network transfer capability is less than the load demand.

b. A fault within a microgrid leading to load loss

Due to a severe storm hitting one of critical feeders, microgrid MG-1 has to lose more than 70% of power generated by its DER and leaving two of its critical loads to be unsupplied. However, the simulation result shows that the developed algorithm has successfully restored load at Bus-11 using the Priority Load Restoration Algorithm to decide closing the switch number 9. Load at Bus-9, on the other hand, remains unsupplied as this load is located in the middle of outage area and has no available path to connect with any source. Each unsupplied load without path to a source, as Load at Bus-9, is stored in a vector, named Islanded_load.

Table 4.9 provides the final configuration to solve this case. Switches 1,2,3,4,5,6,8,9,14,15,16,17,18,19,21,22,23 should be closed, while switches 7,10,11,12,13,20 should remain opened in order to solve the problem. This configuration is shown in Figure 4.4. By this configuration, all loads , except load at Bus-9 that is islanded, are successfully supplied. The minimum switching objective is fulfilled by this configuration by closing switch no. 9. All DERs, other than the ones impacted by the storm, are operating. This means, DER is in optimum utilization. In addition, the sufficiency of this solution has been verified by the converging power flow.

Besides achieving the target of restoring the priority loads, the results show the developed algorithm is able to provide solution with minimum switching action. Another interesting fact for this result, the algorithm chooses to close switch No. 9 rather than switch No. 13 in order to restore load at Bus-11. This result demonstrates the ability of the develop algorithm to prioritize load restoration using the sources from the same microgrid before connecting with another microgrid in the neighborhood. The success on identifying unsupplied load and promptly restored maximum number of load using the developed two-stage algorithm show the self-healing criteria are achieved and grid resiliency is improved.

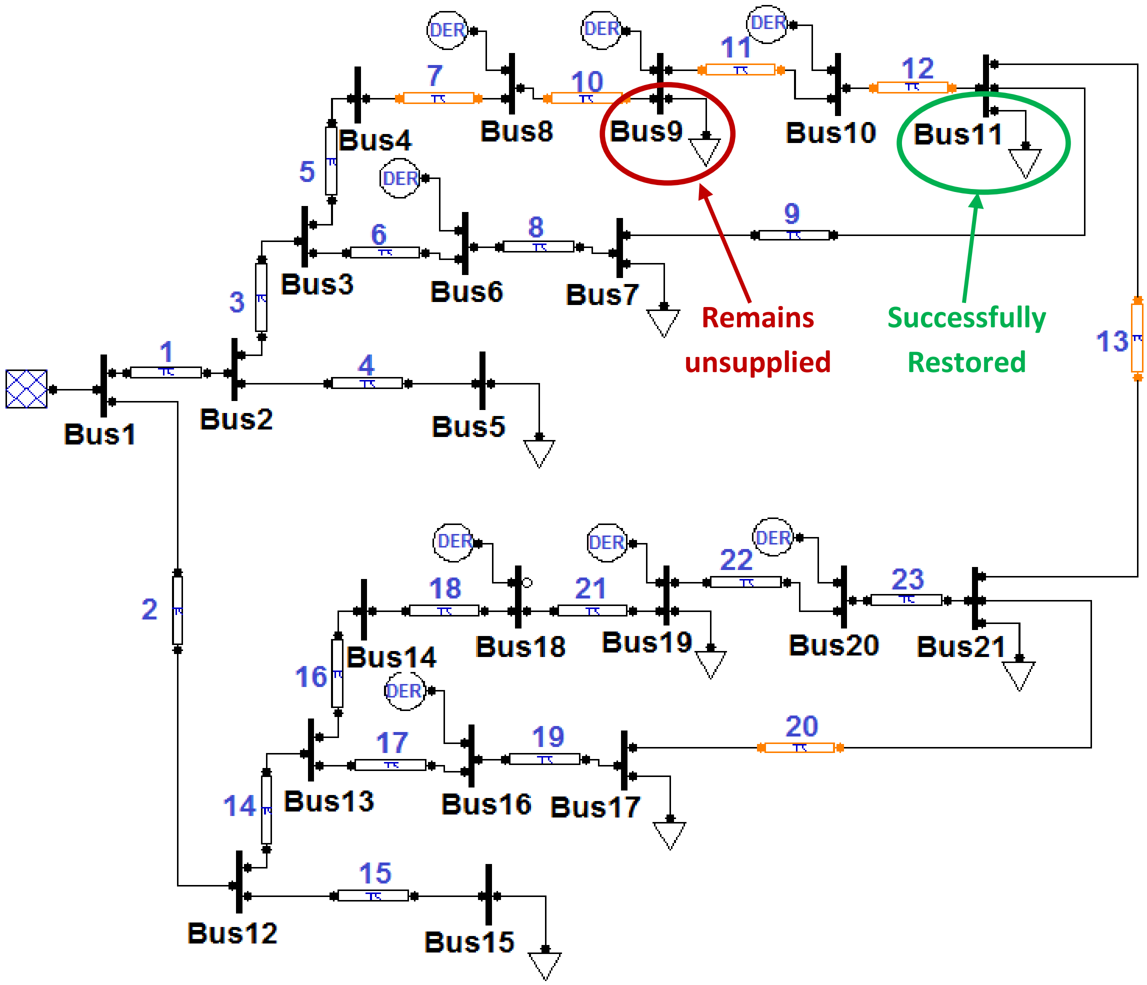


Figure 4.4 Solution of Case Study 2

c. A fault within a microgrid when two microgrids are islanded

In this case study, both unsupplied priority and non-priority loads exist. However, the neighboring microgrid does not have enough power to support both loads and have to choose which one to be supported. The results shows that the developed algorithm chooses to supply priority load rather than the non-priority load as expected.

The simulation results presented in Table 4.9 shows the configuration to solve this problem, where switches 3,4,5,6,7,8,9,10,12,13,16,18,19,20,21,22,23,24,25,26,28,29,30, 31,32,33 must be closed, while switches 1,2,11,14,15,27 must be opened. This configuration can be clearly seen in the following Figure 4.5.

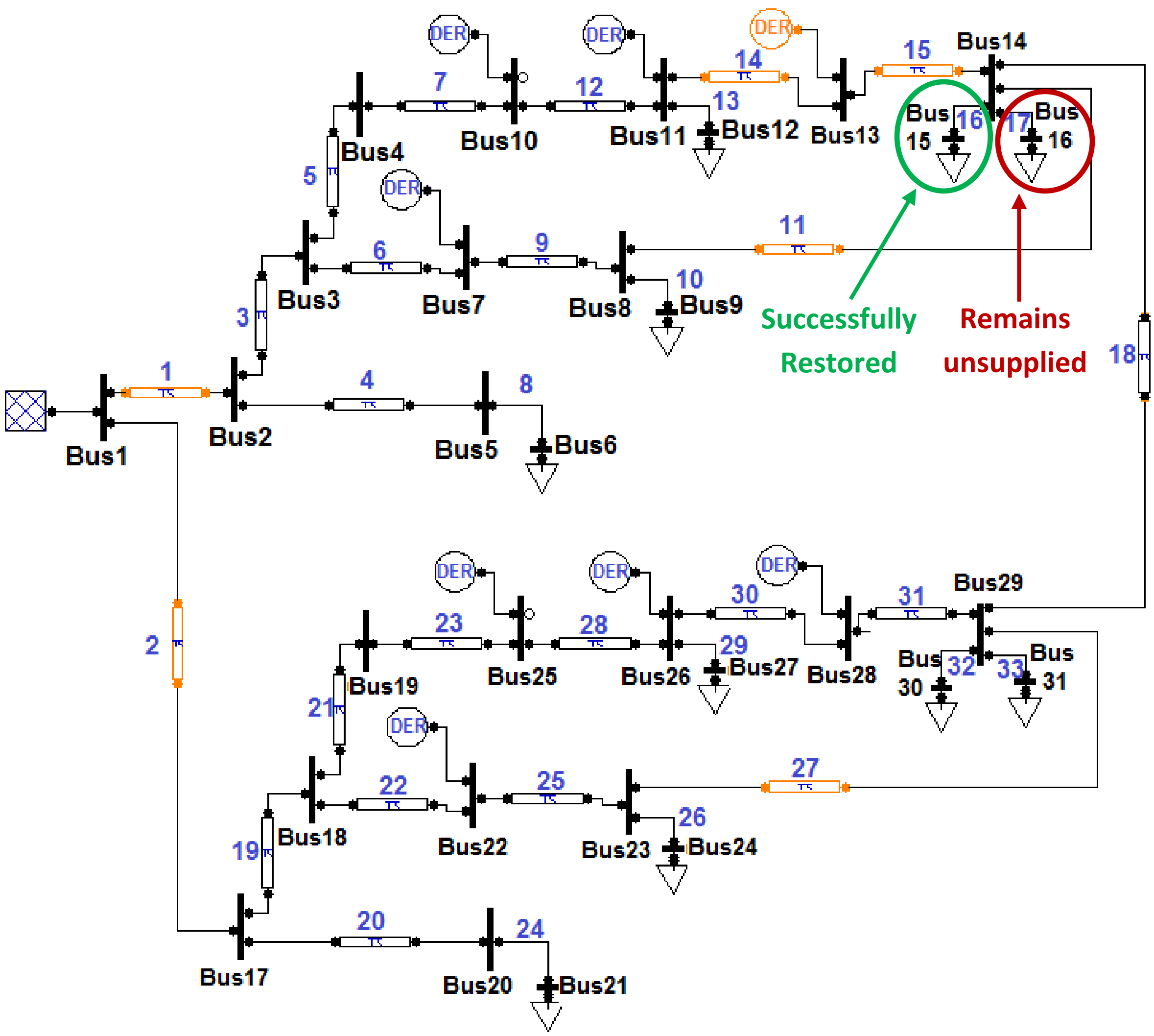


Figure 4.5 Solution of Case Study 3

The algorithm starts by finding the path to restore the unsupplied priority load at Bus-15. The output of priority load path reported five different possible paths to be chosen. The first path, showing bus number 15-4-8-7 returns a non-converging power flow. Hence, this first path is not the solution to this case. The second potential path, showing bus number 15-14-29-28, causes the system power flow to be converged. Since the power flow is converged, path 15-14-29-28 is declared as the solution to restore the priority load at Bus 15. The algorithm then continues to restore non-priority load at Bus-16. While keeping the priority load path in closed position, the non-priority load restoration algorithm searches for potential solution. After the stop criteria is achieved, the personal best of each individual returns as a potential solution. The process is continued with verification of the potential solutions using power flow calculation. However, as no solution returns a converged power flow, the non-priority load at Bus-16 remains unsupplied.

Though the algorithm cannot restore all unsupplied loads due to limited available power, it has successfully restored the maximum possible number of loads. This solution is found by having only 1 switching action, which is closing switch no. 18. The other objective to maximize the utilization of DER is also achieved by the solution provided.

Since not all unsupplied loads are restored in this case, the ability of the developed algorithm to restore partial load due to limited available power in the neighboring microgrid are demonstrated in this case study. This case also shows the ability of this algorithm to restore the priority load at Bus-15, rather than the non-priority load at Bus-16. In addition, the result shows that the developed algorithm has to ability to solve the problem by transferring the load of microgrid MG-1 to microgrid MG-2 while maintaining secure operations for both microgrid systems proven by the converged power flows. The decision-making framework in the case of limited available power in the neighborhood has been successfully presented in this case, by choosing to supply the priority loads, rather than the non-priority loads. Accordingly, the grid resiliency improvement using the developed two-stage algorithm is also presented in this study.

4.6 SUMMARY

This chapter has described three different case studies, which are used to evaluate the performance of the developed two-stage method. The discussion and analysis of the simulation results are also presented to evaluate the contribution of the developed algorithm in multiple microgrids operation, reliability, and resiliency.

4.7 REFERENCES

[1] C.M. Colson, M.H. Nehrir, and R.W. Gunderson, "Distributed Multi-Agent Microgrids: A Decentralize Approach to Resilient Power System Self-healing," in IEEE 4th Int. Symp. on Resilient Control Systems, Boise, ID, 2011, pp. 83-88.

[2] F. Dong, T. Konstyniak, and B. Lam. "Dealing with Power Flow Solution Difficulties. "Internet: http://w3.usa.siemens.com/datapool/us/SmartGrid/docs/pti/2012March/PDFs/Dealing_with_power_flow_solution_difficulties.pdf, March 2012 [Nov. 18, 2014].

CHAPTER FIVE: CONCLUSIONS AND FUTURE WORKS

5.1 INTRODUCTION

This chapter concludes the work by presenting the research that has been conducted, and future research direction in comparison to the thesis objective. The contribution of this thesis is also presented as well as the possible future works in order to increase reliability and resiliency with multiple microgrids.

5.2 CONCLUSIONS

The research on a multiple microgrids reconfiguration for grid resiliency has been conducted in this work. This research has successfully developed a reconfiguration formulation for multiple microgrids to maximize the energized load under fault condition while considering load priority and resiliency requirements as reported in Section 3.2. In addition, the solution approach to the reconfiguration formulation in the multiple microgrids using the two-stage algorithm has been developed, tested, and validated on three case studies. The results of all case studies reported in Section 4.4 have shown that the algorithm is consistently improving grid resiliency by maximizing the total energized load in a multiple microgrids cluster while minimizing switching operation and maximizing the utilization of DER as part of the recovery action. However, this research can be improved further by considering the automatic voltage/frequency load-shedding algorithm and the ESS.

5.3 RESEARCH CONTRIBUTIONS

This research has contributed to the multiple microgrids operation, reliability, and resiliency through 1) formulation of the reconfiguration problem in multiple microgrids, 2) development of two-stage algorithm as the solution for reconfiguration in multiple microgrids, and 3) simulation and analysis of multiple microgrids reconfiguration case studies using the proposed method.

5.4 FUTURE WORKS

Possible research studies following the developed algorithm in improving the multiple microgrids reliability and resiliency are as follow:

i) Multiple microgrids reconfiguration with energy storage systems (ESS) and load-shedding algorithm

The study of multiple microgrids reconfiguration in this thesis is excluding the presence of ESS and load-shedding algorithm. As most microgrids these days incorporating at least one ESS into their system, studying the influence of ESS charging and discharging dynamic to the improvement of grid resiliency will be an important as well as interesting future research. In addition, incorporating automatic under voltage/under frequency load-shedding protection into reconfiguration is beneficial to provide alternatives recovery action for priority loads.

ii) Multiple microgrids reconfiguration with several level of load priority indexes

This work considers only two load priority indexes: priority and non-priority. While in real world application, there are more than two different load priority indexes. This algorithm can be adapted for simulation and analysis of more than two load priority indexes (e.g., non-priority loads, priority load 1, priority load 2, priority load 3, and soon) to see if multiple microgrids will still consistently improve grid resiliency.

iii) Design of Switching Scheme and DG Location for Maximum Resiliency

After network topology during fault condition has been reconfigured, developing the design of switching scheme and DG location for multiple microgrids reconfiguration is another important research opportunity to achieve maximum resiliency.

iv) DER Weighting Factor to Decide which DER Unit Should be Maximized

In order to get full advantages from the DER penetration in the microgrid, weighting factor for each DER needs to be calculated, for decision-making purpose.

v) An Updated Two-stage Algorithm

An updated two-stage algorithm is another possible future work. This algorithm will have a benefit in finding an optimal solution. The first stage of this algorithm will use the path searching method, restore the priority load as soon as possible. This step is treated as a temporary solution. The second stage, using the APSO, will try to find the most optimal solution for both priority and non-priority loads. Once the solution of the second stage is found, the multiple microgrids configuration has to be updated using the output of the second stage.

vi) Hierarchical PSO for the Multiple Microgrids Reconfiguration using Agents

Combining the present work with multi-agent software tools will help with improving the coordination between microgrids and making it distributed and autonomous control. This improvement in multiple microgrids reconfiguration, which will benefit towards the system's reliability and resiliency is considered challenging and possible research extension.

vii) Economic Analysis for the Multiple Microgrids Reconfiguration

The economic value of having a microgrid in a system has been an interesting discussion among many experts, especially since the return on investment (ROI) of microgrid is highly dependable on the operation optimization and physical assets utilization [1]. The impact of operating neighboring microgrids as a cluster as described in this thesis to improve the economic value of the microgrid itself can be a valuable topic to be researched.

5.5 SUMMARY

This chapter provides conclusions and the list of research contributions. The list of further research possibility as well as its importance in multiple microgrids operation is also presented in this Chapter. Lastly, hopefully this thesis will bring valuable contribution to the development of multiple microgrids operations.

5.6 REFERENCES

[1] F. Farzan, et al., "Microgrids for Fun and Profit," IEEE Power and Energy Magazine, vol. 11, iss. 4, pp. 52-58, Jun 2013.