ANALYZING THE IMPACT OF ENERGY STORAGE SYSTEM ON DISTRIBUTION SYSTEM

A Thesis by

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DEDICATION

To my beloved parents, husband for their

unconditional love and support

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would like to thank my adviser, Pingfeng Wang, for his guidance throughout my research years. I would also like to extend my gratitude to members of my committee, Dr. Krishna Krishnan, and Dr. Visvakumar Aravinthan, for their helpful comments and suggestions on my research work. To all my colleagues in the Reliability Engineering Automation Laboratory (REAL), I consider it a privilege to have worked with all of you. Thank you for your assistance and friendship.

ABSTRACT

Modern lifestyle has increased the electrical energy demand. with the increase of power demand, the attention on the renewable resource has also increased due to their environmental and economical; benefits. the renewable resources, on the other hand, are dispatchable generation units meaning that are not controllable in case of producing power, we have sun radiation during the day but not at nights thus, the using the renewable resource might affect the reliability directly. with the increase in demand and technology power system is expected have high reliability.

battery energy storage is being used in microgrid and distribution power system to shave the peak load of the system and enhance the reliability of the system. In this thesis, the focus is optimizing the allocation of ESS in MG with the renewable resources penetration

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1 CHAPTER 1

1.1 Introduction

To maintain the life of the human community, and in order to facilitate the life, many important inventions were discovered, for sure it can be said that the most important of these inventions is electricity, which actually our today's life is depending on that, we can understand the role of electricity in our lives better in time of power outages. Failure happens in electricity power, some failures caused by human mistakes or it can be a weather event, a mechanical problem, etc. vulnerability is a weakness in the system that can be exploited. Electricity can be obtained from different methods, some are renewable energy resources such as wind power, solar power, and some others are nonrenewable energy resources such as natural gas. In today's life the increase of fuel price, the reduction of fossil fuel resources, and the need of reducing the CO_2 emission have increased the necessity of the usage of renewable energy sources (RES) in power systems.

To produce the electricity some actions, need to be taken, the electrical power system is broadly divided into three parts: generation, transmission, distribution system. Generation system is the first step of the electricity production, the power generated in the generation system will be transmitted by the transmission system. In a transmission system, set of wires which are called conductors carry electric power from generating plants to deliver power to customers. Transformer decreases the voltage of the power in distribution lines at numerous substations. Transferring the produced electric power over a long distance with minimum losses (efficiency) make it able to transport power through rural areas also minimizing harm to people and animals are some of the transmission system's goals. Distribution system is the last stage in delivery of electric power, it carries electricity from the transmission_system to individual consumers. Distribution system compared to the other two parts is more important in case of being related to the customers directly.

The reliability of distribution system has been an interesting topic; thus, the objective is to design a system to minimize the number of customers being affected by power system failures. With the growth of renewable resource penetration in power system, due to its environmental and economic benefits, the necessity of having an energy storage system in power system has also increased. The fluctuation in renewable resource could affect the system reliability, these resources are called uncontrollable energies which mean the output power will be affected by the environmental changes. For instance, at night the output power of solar energies is equal to zero and cannot be trusted to satisfy the demand.

In this research, the impact of having the energy storage system and the role of ESS in enhancing reliability has been analyzed. Here we also indicate some of the most important reliability indices in the distribution system and define the important role of micro-grids in improvements of the reliability of the system.

2 CHAPTER 2

2.1 Literature Review

The micro-grid, as defined by the U.S. Department of Energy, is ‘‘a group of interconnected loads and distributed energy resources (DERs) 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 modes’’ [1-4] distributed energy resources (DER) are small power sources that can be used to provide power necessary to satisfy demand [5-8]. From the definition, micro-grids are a backup generation for the grid, but MGs are actually more than that, not only they provide a wider range of benefits but also are significantly more flexible than a backup generation. Micro-grid is able to operate in two modes (grid-connected and islanded mode), which is a reliability improvement factor for the power system. What makes the study of the micro-grids even more interesting is the existence of renewable resources like wind and solar as a cost-efficient source of power, thus the developments of a renewable resource in micro-grid are one of the extensively studied topics in literature. Improving the solar energy generation with the maximum power point is the objective of many articles [9]. The existence of the wind and solar in micro-grid apart from their magnificent role in producing the cost-efficient, clean energy, would bring some challenges, increase the uncertainty and also decrees the reliability of the system because their nature solar and the wind are uncontrollable energy resources. The question we want to address here is knowing the fact that micro-grid is an undeniable factor in improving power system resiliency, how could we improve the reliability of a micro-grid included renewable resources. Later in this Chapter, we address some of these challenges and discuss the proposed methods to tackle these challenge in literature.

2.2 Elements of Micro-grid

The main components of the micro-grid are the PV and/or wind generator, the batteries energy storage, the customer load, the main grid, and the electronic convectors as shown in Figure 1. Having different types of components in the system makes if the more complex system, thus the interconnection of these components in an optimal way is the objective of many articles.

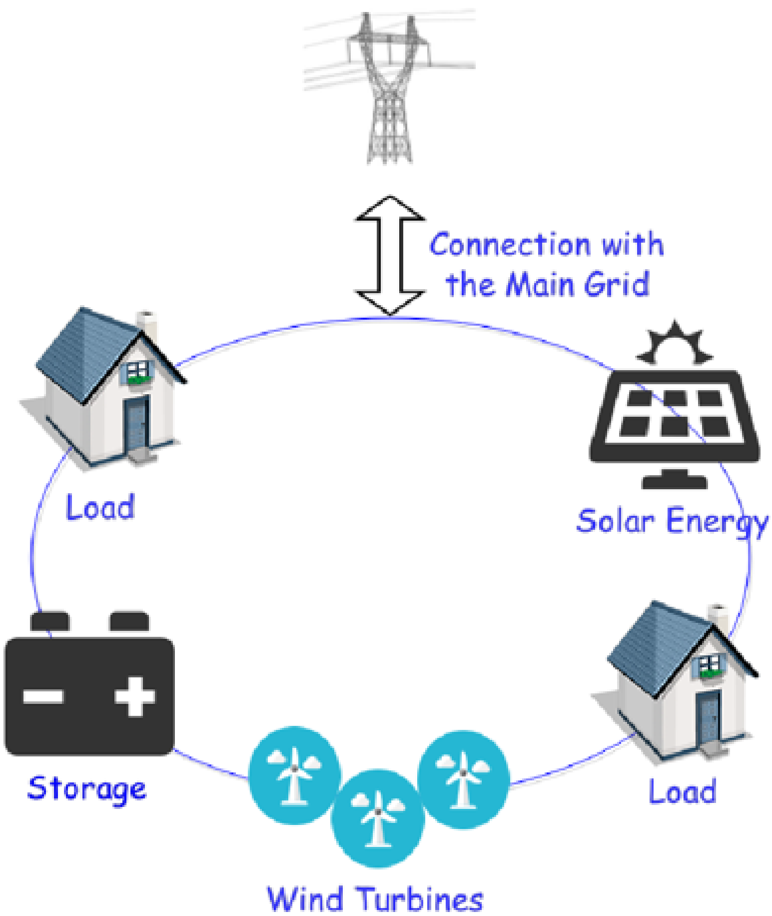


Figure 1. Micro-grid components

2.3 Micro-grid Optimization

When we are talking about optimization it is important to illustrate what is the objective here and from which side we are optimizing, for instance minimizing the operational cost from customer side or maximizing the profit from owner side. Micro-grid can operate in two modes; the first one is grid-connected mode and the second one is islanded mode. For sure, operating mico-grid in islanded mode is the most outstanding feature of this system, because it can provide a good solution for supplying power in case of an emergency. Today's micro-grid consists of different types of distributed energy resources and energy storage system, contributing these different type of energy resources will increase the system complexity. As the complexity increases the reliability of the system decreases. A management strategy is needed to control the system performance. Also, different types of energy resources can be involved in micro-grid. To control this complexity, Yao et al. [10] studied about micro-grid control and structure techniques to minimize the operation cost and maximize the reliability of the system. In the grid-connected state micro-grid is connected to the main grid and power transfer between micro-grid and grid, in islanded operation however the micro-grid is disconnected from the grid and micro-grid operates without the connection to the grid. The switching between two modes is a challenge that needs to be modified, In [11, 12], the micro-grid operation is studied in island mode, and they did different simulations to ensure the micro-grid stability.

2.3.1 Micro-grid Islanding

The outstanding feature of micro-grid is the ability to operate without being connected to main grid, islanded mode for micro-grid is for economic and reliability purposes, during any interruption or failure in grid utility the micro-grid will switch to islanded mode and based on its characteristics a reliable and uninterrupted supply of power demand is maintained by the local distributed energy resources available in micro-grid. In [13], a control strategy is proposed for islanding detection and load shedding in a grid-connected and islanded mode of the micro-grid. Another key factor that could affect the reliability of the system is having an energy storage system. In today's micro-grid battery is added to increase not only improving the reliability of the system by storing the excess energy produced by renewable resources, but also to minimize the total cost of the system.

3 CHAPTER 3

3.1 The Impact of Battery on Micro-grid Performance

It is difficult for the micro-grid to maintain stability after a failure happens in the system and micro-grid temporary being disconnected from the main grid and operates in islanding mode without any battery storage. The application of battery storage will considerably improve the micro-grid performance and thus, the performance of the renewable resources will be increased as well. Energy storage is the key to realize the full positional of micro-grid.

Energy storage system present possibilities for DG producers, customers, etc. Analyzing the impact of battery in the system would improve the performance of micro-grid. Finding optimal allocation of ESS is a complex problem. In this section the operational decision-making problem for a battery energy storage system in the grid-connected micro-grid has been studied, Dynamic programming is employed as a problem-solving framework to find the battery scheduling with minimum costs, Battery costs due to degradation is considered in the optimization. State of charge of the battery (SOC) is the quantity of charge stored in the battery at a specific time and state of health of the battery is related to the aging process of the battery.

$$SOC = \frac{C(t)}{C_{ref}(t)} \tag{0.1}$$

$$SOH = \frac{C_{ref}(t)}{C_{ref,nom}} \tag{0.2}$$

where $C(t)$ is the capacity of the battery at time t, and $C_{ref,\,nom}$ is the nominal capacity of reference which is given by manufacturer data sheet and C_{ref} is the capacity of reference [14]. In this optimization problem, the objective function which is shown in Eq. (1.3) is obtained with Dijkstra algorithm. In Dijkstra algorithm, the shortest path from initial node to destination node will be calculated based on the lowest weight of the arc in this example the cost in the weight of each arc.

$$\mathrm{Cos}\,t = \sum_{i=1}^{i=144} Load_i * EP(t_i) * 10/60 \tag{0.3}$$

where $EP(t_i)$ is the energy price at time t. The resolution in the scale of time is 10 minutes for 24 hours with respect to defined constraints for the optimization problem. SOC of the battery is between 20% and 90%, the initial and final SOC for the Dijkstra algorithm has to be 50% for maximum flexibility on the algorithm. Degradation of the performance of battery during the aging process has been modeled Figure 2. In Figure 2, ΔSOC_{ij} represents the difference between the state of charges between node i and node j.

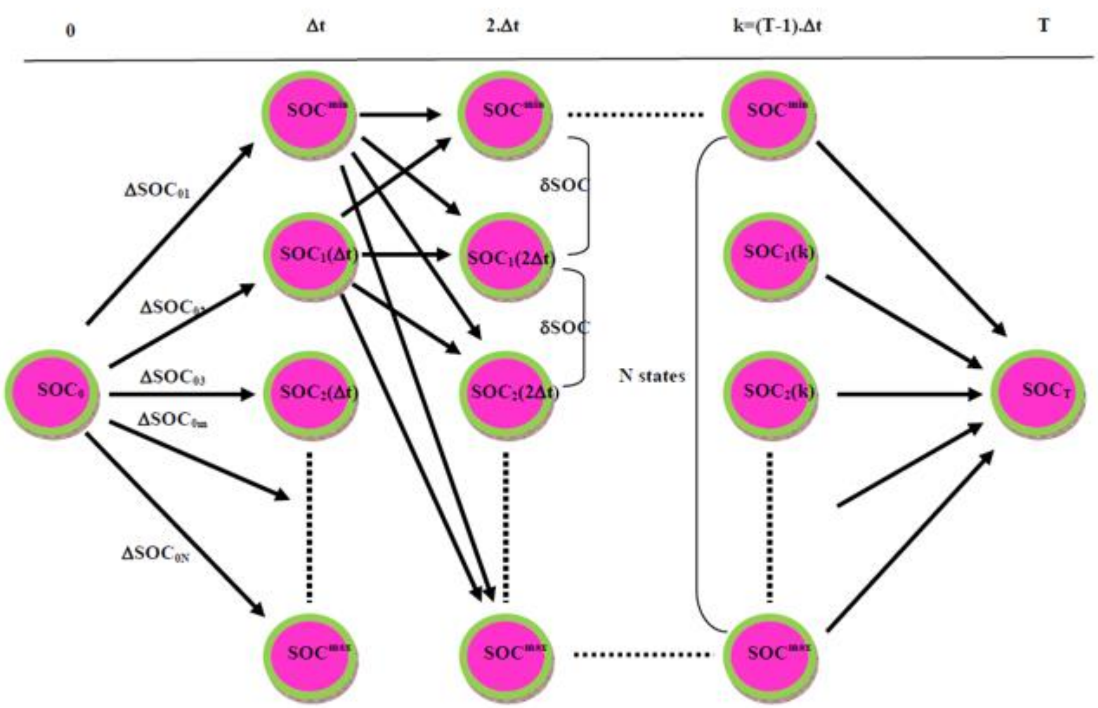


Figure 2. battery SOC level

The obtained optimal scheduling of battery is shown in Figure 3. Figure 3 indicates that the battery will be charged when the electricity market price is low and distiches when the electricity market price is low. Based on the electricity market price, as shown in Figure 3, the battery will be charged in early hours in the morning when the electric market price is low and will be discharged at first peak load hours in the morning. This process will continue till the midnight where battery must have 50% SOC level.

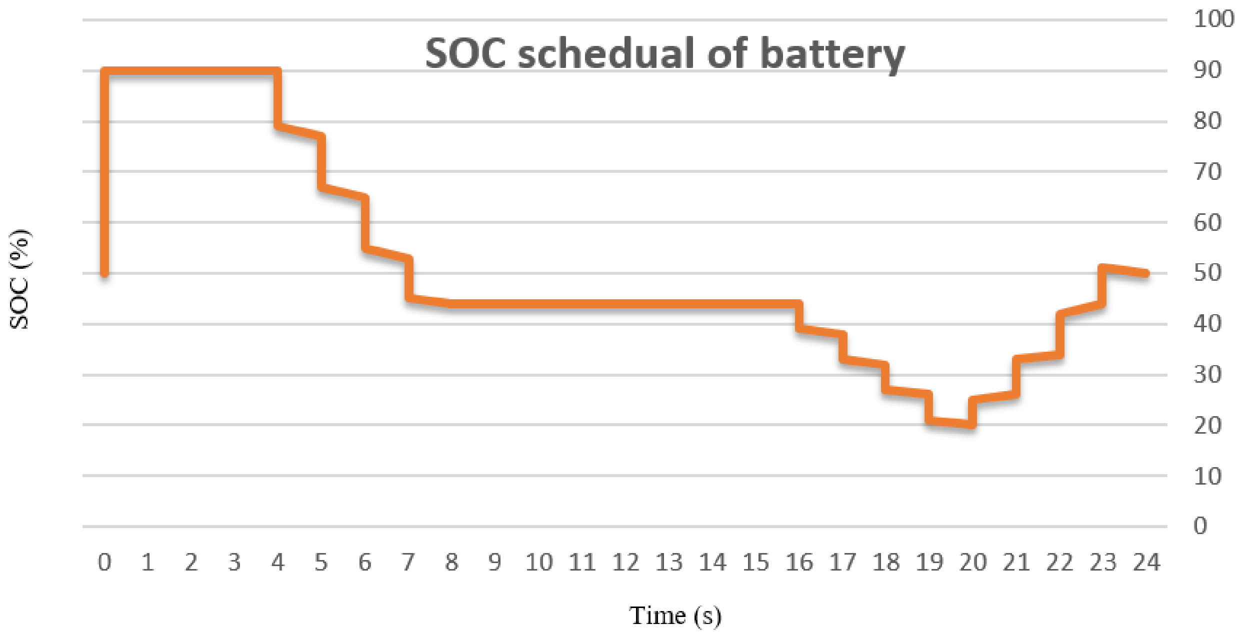


Figure 3. SOC schedule of battery

4 CHAPTER 4

4.1 Energy Storage System in Power Distribution System

Energy storage, in theory, is used in the system to provide stability for the system, for instance energy storage in power system can optimize generation, transmission, and distribution, from integration of renewable energy generation to demand response programs improving distribution losses and performance of the system, can be considered as the highest value for energy storage [15]. In the recent years, the use of renewable sources such as wind power into the power system network has been increasing. Therefore, power systems have faced serious concerns over their operation in terms of reliability.

Integrating energy storage system devices into the power system is one of the solutions being proposed to overcome this concerns in power systems. The profit margins of wind farm owners could also be increased by using these storage devices in the future. ESS basically could present possibilities for the distribution system to have better performance in case of failure or outage in the system. In previous chapters, the necessity to have ESS in today's Micro-grids and the optimal allocation of the battery have been studied. The optimal sizing and placement of the battery in the system have been defined as another challenge in this area. On the other, it is economically important to have the minimum size of the battery. Thus, the placement of the battery in the system would be considered as an important issue.

In case of failure in distribution system when the system is temporary being disconnected from the main grid, considering the location of failure the whole system may be shut down. the distribution system normally has radial architecture, so based on the location of the battery, the loss of load could be controlled. to obtain an economical ESS, a battery sizing strategy has been developed focusing on decreasing the peak load in power distribution system.

4.2 Multi-objective Genetic Algorithm Optimization

Real world optimization problems are often not solvable by only analytical means because of their complexity. Evolutionary algorithms which use mechanisms inspired by paradigms from nature are particularly used to solve these problems. Because these algorithms are derivative-free and population-based methods, they are not as prone to getting trapped in local minima. Most practical optimization problems are inherently multi-objective ones [16-18]. A multi-objective evolutionary optimization which is a relatively new area of research in evolutionary computation is a rapidly growing area for solving optimization engineering problems. In this section, the multi-objective Genetic algorithm has been explained to be used in optimal sizing and placement of EES.

The genetic algorithm is a method based on the process that drives biological evolution which is a natural selection and it has been used for solving both constrained and unconstrained optimization problems. It is called an evolutionary algorithm because it repeatedly modifies a population of individual solutions. At each step, some of the solutions are selected randomly to be parents. Parents will be selected to produce children based on the ranking procedure. The algorithm ranks the solutions based on the fitness function and the fitter solution is more likely to be selected. This process continues till it evolves toward an optimal solution. In multi-objective problems, the ranking procedure is more complex. In this study, Pareto optimality has been applied to identify the fitter solutions. Pareto optimality rank the individuals in a manner such that the non-dominated individuals of the population have a lower ranking, and so, a higher probability of being selected.

Considering x_1 and x_2 are two selected solutions, x_1 dominates x_2 if solution x_1 is no worse than x_2 in all objectives, and solution x_1 is strictly better than x_2 in at least one objective. In this case, we can also say that x_2 is dominated by x_1.

The non-dominated set of the entire feasible solutions is called the Pareto-optimal set. The boundary defined by the set of all point mapped from the Pareto optimal set is called Pareto Front.

4.3 Case Study

Over the years the reliability test systems such as the IEEE Reliability Test System (RTS) and Roy Billinton Test System (RBTS) have been used extensively by researchers, as a benchmark system, for reliability assessment and other developments in the field of probabilistic applications in power systems.

A part of RBTS has been considered here as the case study. Based on the radial structure of the RBTS system shown in Figure 4, there are three feeders in parallel to each other, where feeder 1 has 9, feeder 2 has 8 and the third feeder has 3 nodes.

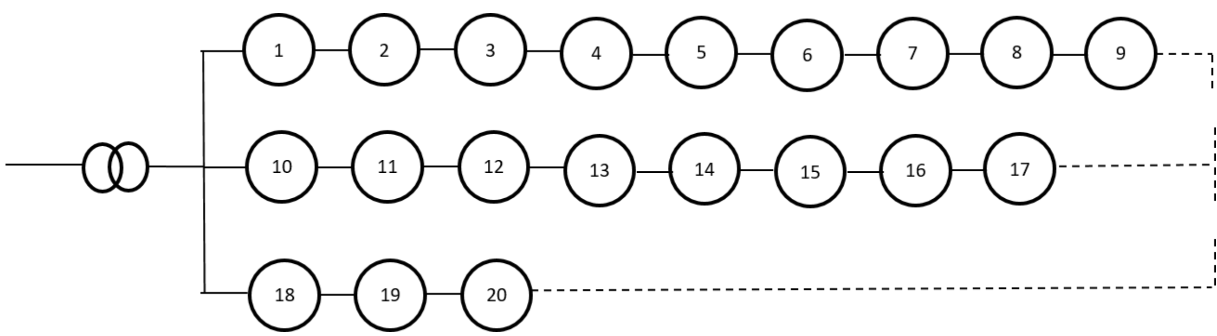


Figure 4. Structure of the RBTS system

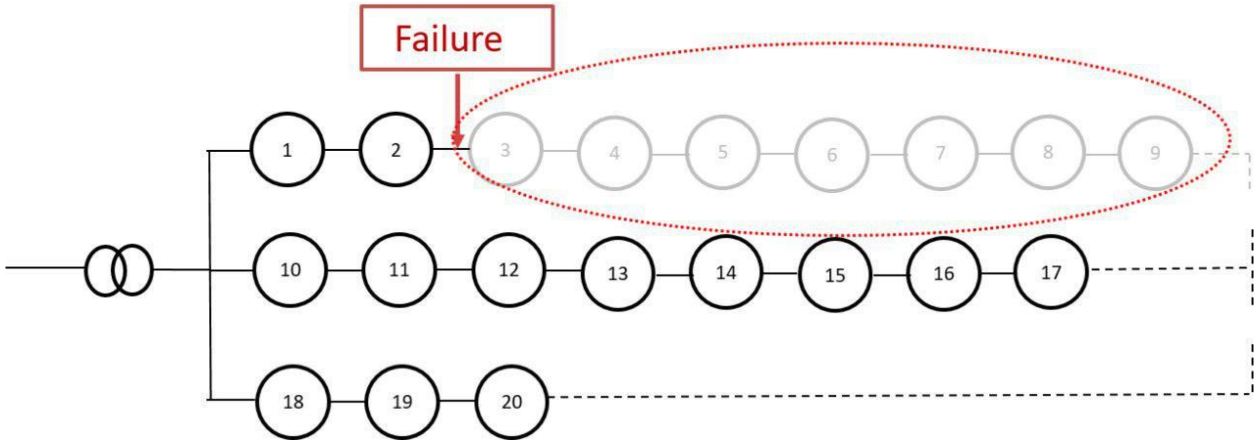


Figure 5. Failures in the structure of the RBTS system

Normally, as can be seen in Figure 5, when failure happens, based on the location of the failure, the system will face massive loss of load and the reliability of the system will decrease.

The battery energy storage could help to improve the reliability of the system by covering some of the load demands in case of emergency. The main objective here is to propose a method is to optimize the location and size of the battery and drive a cost-benefit analysis when a distributed system faces failure.

Basically, there are two parameters in this study that needs to be determined. One of them is the load on each node (L), and the second parameter is the number of batteries that can be used without any cost (N). The cost that will be added to the system if there are more than N number of batteries based on the five different scenarios can be seen in Table 1.

There are two objective functions in this case study. One is to minimize loss of load in the system and the other is to minimize the costs of batteries.

Table 1. Different Type of Scenarios for Batteries

Scenario	0	1	2	3	4
Description	No battery	25 MW battery	50 MW battery	75 MW battery	100 MW battery
Cost	0	250 $	500 $	750 $	1000 $

The costs of batteries are calculated in this study based on their capacities. Respectively, 25 MW battery has 250$ cost, 50 MW has 500$ cost, 75 MW has 750$ cost and 100 MW battery has 1000$ cost.

The 20 components in the system have failure rates and Mean Time To Repair (MTTR) based on Table 2. The failure of components in one year has been considered in this case study.

Table 2. Failure rates and MTTRs of components

Comp. No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Failure rate	5	8	5	9	5	6	7	9	8	8	5	6	5	9	5	6	7	6	8	5
MTTR	0.1	0.2	0.3	0.3	0.2	0.1	0.2	0.3	0.2	0.2	0.1	0.2	0.3	0.1	0.2	0.2	0.2	0.3	0.2	0.2

4.4 Optimal Sizing and Placement of ESS

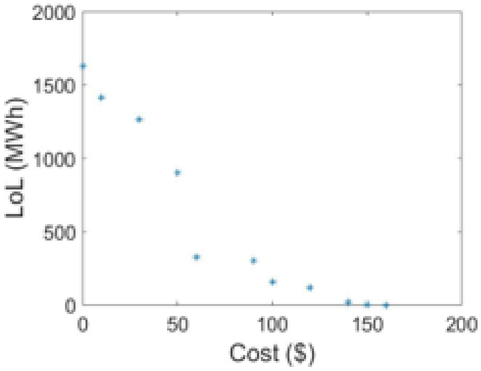
The multi-objective genetic algorithm optimization as explained in Section 4.2 has been used in this study to find out the best combination of scenarios of batteries to be used in the system to satisfy the minimum loss of load (LOL) and minimum cost of batteries [19]. There is a tradeoff between these two objectives. While it seems that more usage of batteries in the system with higher capacities will decrease the LOL, the cost of the system will increase [20].

Two values for parameter N (5, 10) and three values for parameter L (100, 200, 500) have been considered in this study in order to find out the impact of these parameters on the results. Therefore, there are 6 different cases which need to be considered. The multi-objective Optimization has been implemented for each case. Figure 6 shows the Pareto front for each case.

To be more specific and clear about the combinations of batteries that form the Pareto Front, the details about the batteries scenarios in the Pareto front where the cost is the lowest and the cost is highest among the Pareto Front cases has been shown in Table 3 for each case of Figure 6.

The results in Table 3 shows that the minimum cost on Pareto Front happens when then number of batteries that are used is not more than the parameter N, for instance in case A, where N=5, only on 5 nodes there are batteries for the minimum cost case, and on case D, where N=10, only on 10 nodes there are batteries for the minimum cost case. By increasing the load on each node, as can be seen in Table 3, the size of batteries and the number of batteries that makes the maximum cost (minimum LoL) on Pareto Front will be increased.

Therefore, based on the results and the parameter studies, it can be concluded that there is a trade-off between the cost of batteries and the loss of load. The cost and loss of load depend on two parameters in this study which are the load on each node and the penalty which is considered for more than a specific number of batteries that are being used.



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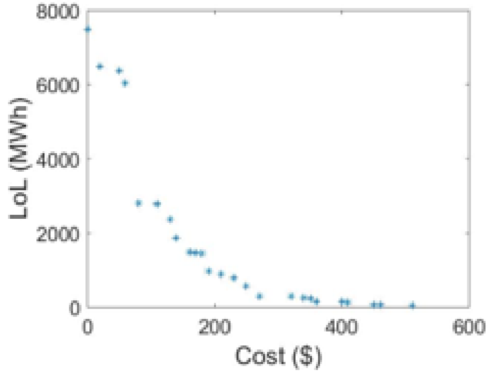

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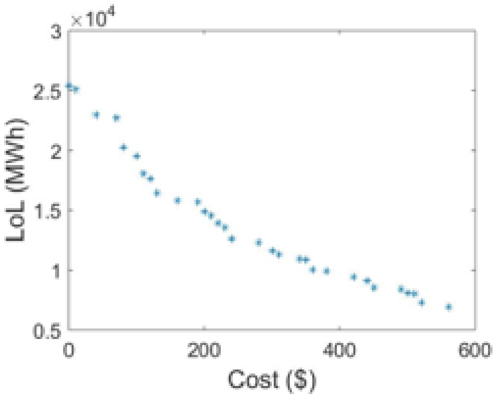

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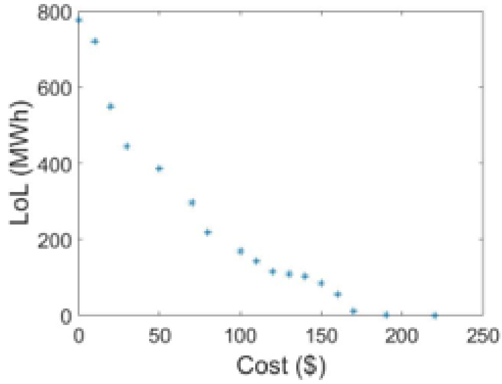

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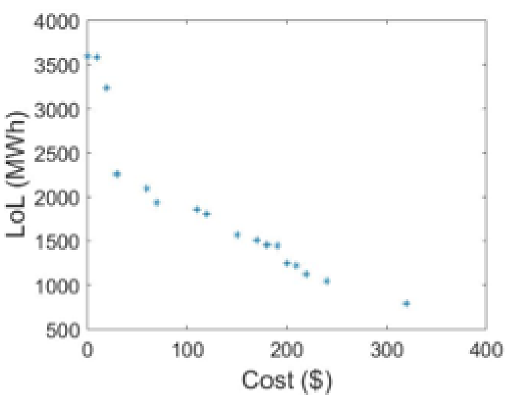

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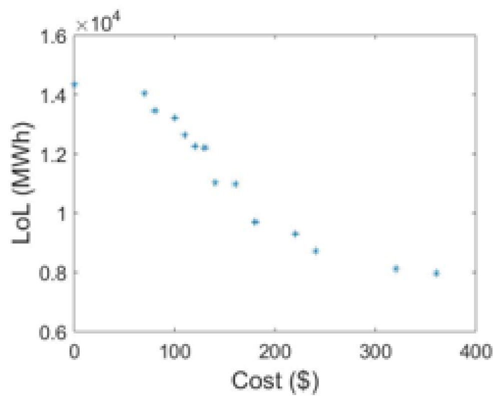

G

Figure 6. Pareto Front results for cases A) P=5, L=100 B) P=5, L=200 C) P=5, L=500 D) P=10, L=100 E) P=10, L=200 F) P=10, L=500

Table 3. The battery size on each component for the highest and lowest cost on Pareto Front

Comp No.		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A	Battery Scenario (Minimum Cost)	0	0	0	0	0	0	4	0	0	0	0	0	0	0	3	3	0	2	1	0
	Battery Scenario (Maximum Cost)	0	0	0	3	4	0	3	3	3	1	0	0	3	0	3	1	3	0	2	3
B	Battery Scenario (Minimum Cost)	0	4	2	0	3	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0
	Battery Scenario (Maximum Cost)	0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	1	3	4	4
C	Battery Scenario (Minimum Cost)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	4	3	0	2	3
	Battery Scenario (Maximum Cost)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
D	Battery Scenario (Minimum Cost)	0	0	3	1	3	0	0	3	0	0	0	3	0	4	1	4	0	1	0	1
	Battery Scenario (Maximum Cost)	1	0	3	3	0	3	3	0	2	0	3	3	3	4	3	4	3	4	4	4
E	Battery Scenario (Minimum Cost)	0	0	0	0	0	0	0	4	2	1	3	3	0	2	2	3	3	0	2	0
	Battery Scenario (Maximum Cost)	0	0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
F	Battery Scenario (Minimum Cost)	0	0	0	0	0	0	4	4	4	4	4	4	4	4	4	0	0	0	0	0
	Battery Scenario (Maximum Cost)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

4.5 Conclusion

In power system, energy storage can be used to provide stability for the system. Power systems have faced serious concerns in terms of their reliability by increased usage of renewable energy sources such as wind power. Therefore, integrating energy storage system in power systems has grabbed lots of attention in recent years. In this study, the usage of the battery as an energy storage has been considered in the case study with 20 nodes and with different battery sizes. The challenge in using batteries is that although battery usage in the system will decrease the loss of lead, it has cost for the system. Therefore, in this study, Pareto ranking with Genetic algorithm has been used as a multi-objective optimization method to solve this optimization problem. Two parameters have been considered in the case study which is a load on each node and the cost penalty for the number of batteries that are used. Results and parameter studies show different combination of batteries that form the Pareto ranking based on the tradeoff between minimizing LOL and minimizing the cost of the batteries on the system.

5 CHAPTER 5

5.1 Future work

There is another aspect to this research area which should be pursued. As we discussed in previous chapters, resiliency in power system is divided into three categories, damage prevention, system recovery, and survivability. System design standards in case of enchasing the power system resiliency need to be considered and studied. Improving resiliency of systems from damage prevention aspect relates to the construction of the system, maintenance, cyber and physical security, although it is impossible to design a system which would be reliable to any natural disasters, finding a realistic balance between costs and potential benefits is what we are looking at this stage. Also, the battery allocation optimization problem is solved for a grid-connected micro-grid, in future we plan to analyze the failure resilience of grid-connected micro-grids with battery energy storage systems and Integration of scheduling of battery energy storage system with the micro-grid operation (grid balancing).

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