A MILP-BASED APPROACH FOR VIRTUAL MICROGRID RESTORATION

BY

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To my father for his continued support and sincere love. To my brothers and sister for their support and inspiration. To my whole family for their wishes and prayers

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LIST OF ABBREVIATIONS

RE	:	Renewable Energy
DS	:	Distribution System
DG	:	Distributed Generators
VPP	:	Virtual Power Plant
EM	:	Energy Market
MILP	:	Mixed Integer Linear Programming
DER	:	Distributed Energy Resources
MIP	:	Mixed Integer Programming
MINLP	:	Mixed Integer Non-Linear Programming
FMSR	:	Fault Management and System Restoration
ISO	:	Independent System Operator
TVPP	:	Technical Virtual Power Plant
CVPP	:	Commercial Virtual Power Plant
SC	:	Soft Computing
MP	:	Mathematical Programming
CI	:	Computing Intelligence

CB	:	Circuit Breaker

ABSTRACT

Full Name : Ali Noor Mohammed Bu Jubarah

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There is a sharp increase in the demand side as a result of technological and civilizational advances, thus power system networks have to be continuously upgraded. This increase has made it difficult to control the system especially when complex system failures occur, resulting in undesirable impacts on the reliability of the network. Renewable Energy sources (RE) are one way to minimize the dependency on the conventional sources to generate electrical energy, which also plays a significant role in increasing the reliability of the system and reducing the environmental pollution.

Integrating RE with other high technological equipment into the conventional distribution system (DS) leads to a system concept known as the microgrid system where it is more reliable than the conventional distribution system stands alone. Also, another concept can be reached by integrating RE with the DS which is known as the virtual power plant (VPP) where new tools and devices need to be incorporated in the system in order to analyze and model the system to work optimally in the energy market (EM). However, the resulted system from the emerge of RE and DS need to be controlled and maintained where it should have the ability to isolate and restore the power when faults happened on the system. Therefore, efficient algorithms must be applied to ensure the optimum restoration of the system.

This thesis studies the smart restoration optimization technique for the microgrid network and the VPP network. The proposed system will participate in the EM during fault management and will be known as the concept of virtual microgrid. Several factors are to be considered in the study like the maximum load demand and the available power supply. In addition, the operation and maintenance cost is an important factor in this study in addition to a load priority. The restoration problem will be posed as a Mixed Integer Linear Programming (MILP) problem and then it will be solved using CVX software to ensure the optimal restoration configuration of the virtual microgrid system. The system will be implemented as an IEEE 13 bus system and it will be assumed to be a smart virtual microgrid system that consist of automated devices such as automated switches, computer based remote control and sensors.

Simulation results of the proposed technique will be shown to demonstrate the effectiveness of restoring the system after faults occurrence by optimizing the power output capacity of the generators and controlling the loads. Remarkable results of the proposed technique are obtained regarding the computational time and accuracy.

ملخص الرسالة

الاسم الكامل: علي نور محمد بوجباره

عنوان الرسالة: استعادة نظام الشبكة الافتراضية الصغيرة استناداً إلى البرمجة الخطية ذات العدد الصحيح

التخصص: الهندسة الكهربائية

تاريخ الدرجة العلمية: شعبان ١٤٤٠ هـ

هناك زيادة حادة في جانب الأحمال الكهربائية نتيجة للتقدم التكنلوجي والحضاري، مما يدعو إلى ترقية شبكات الطاقة بشكل مستمر. هذه الزيادة تجعل من الصعب السيطرة على النظام بسبب حالات الطوارئ وانقطاع الكهرباء المعقدة التي تحدث للنظام والتي تؤدي إلى آثار سلبية على موثوقية الشبكة. تعد مصادر الطاقة المتجددة إحدى الطرق الفعالة لتقليل الاعتماد على مصادر الطاقة التقليدية لتوليد الطاقة الكهربائية والتي تلعب أيضاً دوراً مهماً في الحد من التلوث البيئي.

يؤدي دمج مصادر الطاقة المتجددة مع غيرها من معدات التكنلوجيا المتطورة في نظام التوزيع التقليدي إلى مفهوم نظام يعرف بنظام الشبكة الصغيرة، حيث يتميز بأنه أكثر موثوقية من نظام التوزيع التقليدي القائم بذاته. أيضاً، يمكن الوصول إلى مفهوم آخر عن طريق دمج مصادر الطاقة المتجددة مع نظام التوزيع التقليدي والذي يعرف باسم محطة الطاقة الافتراضية (VPP)، مما يلزم إلى دمج أدوات وأجهزة جديدة في النظام من أجل تحليل وتصميم النظام للعمل على النحو الأمثل في مجال سوق الطاقة. ومع ذلك، يجب التحكم في النظام الناتج عن دمج مصادر الطاقة المتجددة مع نظام التوزيع التقليدي والحفاظ عليه، حيث ينبغي أن يكون لديه القدرة على عزل واستعادة الطاقة عند حدوث أعطال في النظام. لذلك، يجب تطبيق خوارزميات فعالة لضمان الاستعادة المثالية للنظام.

ستدرس في هذه الاطروحة تقنية الشفاء الذاتي للشبكات الذكية (الشبكة الصغيرة) و (محطة الطاقة الافتراضية)، أيضا مفهوم جديد باسم الشبكة الصغيرة الافتراضية مقترح في هذه الاطروحة حيث انه سيشارك في سوق الطاقة وفي نفس الوقت سيقوم بإدارة الأعطال الواقعة على النظام. هناك عدة عوامل يجب مراعاتها في الدراسة مثل استعادة اقصى

حد من الاحمال الكهربائية المتأثرة من العطل ومصادر الطاقة المتوفرة في النظام. بالإضافة إلى ذلك، تعد تكلفة التشغيل والصيانة عاملاً مهماً في هذه الدراسة بالإضافة إلى أولوية الأحمال الكهربائية عند استعادة النظام والطاقة. سيتم صياغة تقنية الشفاء الذاتي كمسألة برمجة خطية ذات عدد صحيح (MILP) وبعد ذلك سيتم حلها باستخدام برنامج CVX لضمان تكوين الاستعادة المثلى لنظام الشبكة الافتراضية الصغيرة. سيتم تصميم وتطبيق الدراسة كنظام IEEE 13 bus، وسيتم الافتراض بأنه نظام شبكات ذكي يتألف من أجهزة آلية مثل المحولات الآلية، وكمبيوترات ذات التحكم عن بُعد وأجهزة استشعار.

سيتم عرض نتائج محاكاة للتقنية المقترحة لإثبات فعالية استعادة النظام بعد حدوث الأعطال من خلال تحسين قدرة الطاقة للمولدات والتحكم في الأحمال. تم الحصول على نتائج ملحوظة من التقنية المقترحة فيما يتعلق بالوقت والدقة الحسابية.

CHAPTER 1

INTRODUCTION

The first chapter of this thesis consists of five sections. Section 1.1 is an overview of the main idea of the problem. A thesis motivation will be shown in section 1.2 while section 1.3 contains the thesis objectives. At the end, the structure of the thesis is presented in section 1.4.

1.1 Overview

Power quality, high efficiency and reliability in energy usage are important subjects in operating and implementing current grids. With the increase of load as well as the need of a high efficient system, more research and techniques are needed to evaluate the reliability and the efficiency of the power network. Moreover, the reliability of the grid is negatively affected by many problems, which can be solved by implementing the smart grid technologies and techniques. The smart grid is a large-scale distributed system that contains many new components like storage units, renewable energy sources, two-way communication infrastructure, and electric vehicles [1]. According to [2], smart grids is defined as an intelligent grid that uses a communication technology and an information of the network status by using control systems and smart meters designed to handle the distributed resources and the un-forecasted load.

There are many advantages of the smart grid in comparison with the conventional grid from both utilities and consumers perspective. At the consumer's side, the system will consist of smart meters that can help the consumer to manage and reduce the consumption of energy during high-energy usage peaks, which leads to reduce the cost of using electricity. On the other hand, to the utilities perspective, the smart grid network can provide more reliable energy service, which decreases the amounts of electric outages and power losses, it can automatically report the location of an outage before the consumers get affected, making the restoration service faster and the status notification to individuals much easier. In addition, smart grid system can provide more efficient system by reducing the cost to produce, deliver, and consume electricity. Furthermore, the integration of renewable energy sources with the conventional system result in a reduction of the environmental emissions and discharges [3]. The smart grids come in different shapes and types like the microgrids, nanogrids, and the virtual power plant (VPP).

In a standard microgrid network, there are number of conventional and renewable distributed sources, several controllable and uncontrollable loads, and some sort of storage sources. These components are together called distributed energy resources (DER). The microgrid network has different types of users, where each type has different priority, such as commercial, industrial, residential and electric vehicles. Figure 1 shows a typical design of the microgrid system and the interconnection with different type of users and generations [4], and shows the two-communication paths between the microgrid and utility grid and the power sources.

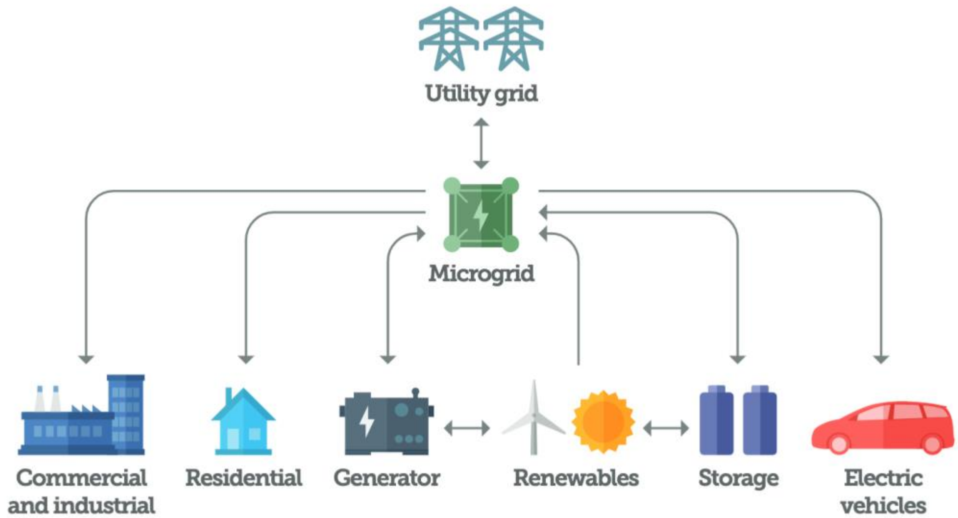

Figure 1.1 Sample system design of microgrid network [3]

One feature of the microgrids network is that it can be operated in an islanded mode where it works separated from the main grid as a single utility to deliver energy to the users during outages. This feature is known as the smart self-healing where it consists of protection devices that can detect the fault location and isolate it from the rest of the network [5]. During faults isolation, switching operation will occur and some of the healthy sections will experience service interruption [6]. Thus, the network must have the capability of applying the smart restoration service in order to restore these healthy areas as fast as possible. However, because of the integration of RE with the distribution system (DS) into the microgrids network, and due to the existence of the advanced devices in the smart grids network such as the smart meter, where it reports the location and size of an outage, the restoration service becomes more flexible and faster to be implemented.

1.2 Thesis Motivations

An important concept of the microgrids is smart restoration, which is defined as the ability of the microgrid to separate the faulted section of the network and restore the optimal configuration of the network using advanced control and monitoring devices and utilizing all the available power from the distributed sources. The restoration problem is usually considered to be multi-objectives and multi-constraints optimization problem. To analyze the network and apply the smart restoration service on the smart grids, many promising approaches of analyzing the system are applicable and mathematical programming (MP) is one of them. MP is a mathematical model of the problem where it is commonly implemented as a mixed integer programming (MIP) problem and evaluated by mathematical softwares. MIP can be categorized into a mixed integer linear programming (MILP), and mixed integer nonlinear programming (MINLP) approaches.

In this thesis, a MILP approach will be proposed to formulate the fault management and system restoration (FMSR). To solve the FMSR problem, different factors need to be considered to find the optimum solution for the problem like the available power supply, the priority of loads, and required maximum load demand. For this thesis, multi-objective functions of the optimization problem must be solved like maximizing the energy restored in the system, maximizing number of customers to be restored, and minimizing the system losses. Also, minimizing the operational and outages costs are important objective functions to be considered when formulating the FMSR as a MILP problem.

The system will be implemented as an IEEE 13 bus system and it will be assumed to be a smart virtual microgrid system that consist of automated devices such as automated switches, computer based remote control and sensors.

There are significant research challenges when it comes to solving the fault management and system restoration problem, which include:

• Using IT infrastructure to inform the facilities of a potential abnormality in the system in order to react before outages occur.

• Using smart meters and smart automation control devices to present real time data about the grid status and to instantaneously alert utilities in the case of failures.

• Locating faults by using monitoring and controlling devices to isolate faulted sections of the network and reconfigure the system.

1.3 Thesis Objectives

The main objective of this thesis is to study and analyze the restoration process of the smart grids with considering the participation of the system in the energy market (EM). The objectives of this thesis can be summarized into three main objectives.

1- To propose a model of the virtual microgrid by integrating the concepts of microgrid and VPP.
2- To model the FMSR as a MILP problem.
3- To test and verify the proposed FMSR model by using CVX software.

1.4 Thesis Contributions

The main contributions of this thesis are as follows:

- Proposing a new model called virtual microgrids that:
  - Integrate RE with the conventional sources.
  - Participates in EM while considering the restoration service.
- Proposing a MILP based approach of the virtual microgrid restoration that:
  - Considers the distribution network constraints.
  - Considers the priority weights of loads.
  - Depends on the time of fault occurrence.

1.5 Thesis Structure

The rest of this thesis is organized in four chapters as follows:

- Chapter 2 provide a comprehensive literature survey divided into three parts. The first part is about the microgrid and its application. The second part is about the VPP and the differences in applications between microgrid and VPP. The last part is about the optimization techniques that used to implement the restoration problem of the smart grids.
- Chapter 3 contains modeling of the proposed system and the different types of DGs. Also, it provides the general formulation of the MILP technique as well as formulating the FMSR and the constraints used in the problem as a MILP approach.

- Chapter 4 discussed the results of the proposed model. Three case studies verifying and implementing the proposed MILP approach.
- Finally, Chapter 5 present a conclusion and a future work related to the thesis work.

CHAPTER 2

LITERATURE REVIEW

2.1 Electric Microgrids

As mentioned in chapter 1, the reliability of the grid can be negatively affected by different factors and the smart grids is one way to solve this issue [7]. A microgrid is one type of the smart grids where it consists of number of conventional generators, and DG sources, several controllable loads, and some sort of storage [8]. A microgrid system can provide a coordinated integration of the RE with the DS network and it provides more reliability to the network. According to [9], the microgrid can operate in two modes: in grid-connected mode and in islanded mode. In grid-connected mode, the microgrid transfer power to other microgrids system or the main grid, while in case of a mismatch in supplying the loads it will import the power from the main grid.

There are two ways for controlling and managing the microgrid [10], centralized approach and decentralized approach. In the centralized approach, one single controller is controlling all the DGs, storage sources and the controllable loads [11, 12]. This approach has the advantages of optimizing the operation of the network due to the complete observability of the microgrid network. However, with the increase number of DGs, it will be more complex to operate the microgrid network optimally [13]. On the other hand, the decentralized approach allows the DGs owners to participate in a market environmental within the microgrid [14, 15]. However, since each part of the system will be treated independently, this may lead to reduce the reliability of the microgrid network and make it hard to implement the system in an islanded mode.

2.2 Virtual Power Plant

According to [16], VPP does not have a fixed definition. In [17, 18], VPP is defined as a combination of micro units that are connected to low voltage DS. In addition, VPP can be defined as an aggregation of different forms of distributed resources that are scattered in a medium voltage network [19]. While in [20, 21], VPP is defined as a multi-technology and multisite diversified entity. However, the most common definition of the VPP is an aggregation of different types of DGs, controllable loads, and sorts of storage sources that form one single entity that will represent all the components of the system in the EM and act as a normal power plant [22, 23]. VPP can participate in EM and trade energy with an entity called Independent System Operator (ISO) [24].

According to [25], VPP has two types in the literature: technical VPP (TVPP) and commercial VPP (CVPP). Based on [26], TVPP concept focus more on the technical side of the network where it combines different parts of the network to accomplish system reliability and stability and provide technical services to the ISO. On the other hand, CVPP represent the parts of the network as single source of energy and participate in EM to trade energy with ISO to maximize its profits [27, 28].

Although microgrid and VPP networks are very similar in concept when it comes to increasing the reliability and the stability of the system; however, there are some differences between microgrid and VPP [29]. Microgrid can operate in islanded mode when there is a fault in the line connected to the main grid, while the VPP cannot operate in an islanded mode. Also, [30] says that the VPP can aggregate DGs sources and the controllable loads to work as one entity participating in EM while the microgrid does not have the feature to join the EM and trade energy.

2.3 Virtual Microgrids

The main gap of the literature is the concept of the virtual microgrid and its applications. Only one reference [31] discussed the theoretical concept of the virtual microgrid and gives a general comparison between the microgrid, VPP, and the virtual microgrids. The reference shows that the virtual microgrid can be defined as the integration of all different types of distributed sources, and storage sources that are coordinated by a control center. In addition, the author says that the virtual microgrid has same characteristic of the microgrid with respect to the main grid, so it can be operated in two modes, the grid connected mode, and the islanded mode. Also, the virtual microgrid is similar to the VPP in participating in EM where it can trade energy with the main grid in both day-ahead market and real-time market. However, the reference only described the virtual microgrid concept theoretically and did not show any technical results.

2.4 Mixed Integer Linear Programming

Many researchers studied the possibility to apply the smart grids on the existing systems and networks and to investigate its effects on the reliability and the efficiency of the system. In addition, several studies discussed the restoration problem of the smart grids and the techniques used to optimize the operation during interruptions [32-36]. The techniques that are used to optimize the restoration problem can be divided into three types, heuristic approach [37, 38], soft computing approach (SC) [39-42], and mathematical programming approach (MP) [43-48].

For the heuristic approach, it is also known as an expert system where the search strategy utilizes the operator’s experience and knowledge to get the best and optimum reconfiguration of the microgrid network. For instant, the work at [37] present a heuristic approach to find the reconfiguration system where it uses an equation that is described as a ratio of power losses and the load demand as an objective function of the problem, it starts as all switches are in an open state and the switch will be closed in case it causes the smallest increment in the objective function. The idea of this research is to reduce the value of the objective function by finding new locations for the switches and it takes less counting effort than sequential switching. Two heuristic procedures are used in [38] in order to define the collection of switches to be opened resulting in minimizing the overall power losses in the distribution systems. However, both researches did not consider the customer priority ranking and the heuristic approach takes more time to restore and reconfigure the system.

SC approach is expanding as a solution for the restoration problem of the microgrid. It is known as a computational intelligence (CI) where it means that a computer would have the ability to understand a particular function from experimental observation. Moreover, it uses inaccurate initial solutions to find the answer of complex tasks like the solution of nondeterministic polynomial problems, for which there is no algorithm that can solve the polynomial problems using an exact solution. There are different SC techniques that were applied to find an answer for the restoration problem, like fuzzy logic [39], particle swarm optimization [40], and clonal selection algorithm [41]. The presented work at [42] proposed a differential evolution algorithm technique where it shares part of the desired power needed to each microgrid network in a scattered technique but it did not consider isolating faults and clearing them in an economic way. Despite the attraction of the SC techniques in many field of studied, applying it to power networks results in three main disadvantages: it required many external variables to be defined for the optimization, does not guarantee the global optimal solution, and sometimes it required an extensive computational time for simple problems.

Because of the large number of control parameters and the difficulty of the microgrid systems, the best way to overcome this issue is to apply a mathematical approach to guarantee the optimal restoration and reconfiguration of the network [43]. MP is a mathematical model of the problem where it is usually formulated as a MILP problem that can be solved mathematically. MIP can be categorized into linear (MILP) and nonlinear (MINLP) approaches. Several researches considered the MILP approach as a technique to solve the restoration problem. The author of [45] proposed an algorithm considering the MILP technique to minimize the cost of the restoration operation of the microgrid network in an islanded mode and to sustain the network stability. The developed model checks power balance and measures the frequency, the system will perform load shedding due to a shortage power resulting from dropping the frequency and becomes less than the limit of the system's frequency to balance the power in the system. In [46], a MILP technique based on the auto reconfiguration of a microgrid system has been developed to optimize the operation cost of the system in a grid connected mode. Furthermore, a centralized energy management system (EMS) has been proposed in conformity alongside the developed MILP approach so that when a fault occurs and a circuit breaker (CB) change the status to open, the system will be reconfigured without considering the opened CB. So, the idea is that all the components of the system communicate with each other and perform the algorithm, after any change in the system's components, the system data is updated by the EMS and create a new schedule for more economical operation.

Another research solved the restoration problem of the microgrid network by applying two stages of MP: MILP and MINLP [47]. The research firstly fined the optimal configuration of the system by solving it as a MILP problem, then it solved a MINLP problem to modify the steady state operating point of the topology found in the first stage like adjusting the continuous electrical parameters and find the optimal load shedding. Load management was considered in this work where the load can be altered during optimization process. However, a static voltage was used for all the nodes of the system while considering the power flow. In addition, applying MILP then MINLP results in not finding the global optimally restoration of the system and that because not all variables of the problem are considered at the same time.

CHAPTER 3

SYSTEM MODELING AND PROBLEM FORMULTION

This chapter consist of different sections describing the system model, MILP methodology and the mathematical formulation of the problem of FMSR. Section 3.1 explain the used system and the modification that was applied on it such as the location of different load types and generations sources. A general formulation of the proposed MILP technique is presented in section 3.2 while the mathematical formulation of the FMSR problem with the constraints as a MILP problem are in section 3.3.

3.1 Description of FMSR Problem

The main objective of this research is to analyze and formulate the fault management and system restoration (FMSR) problem of the virtual microgrids network as a MILP problem. There are many parameters that need to be considered in solving the FMSR as a MILP problem. Therefore, it is important to understand the concept of the proposed FMSR problem and what are the objective function that will be used to solve the FMSR problem as MILP along with the constraints and the control variables.

3.1.1 Objective Functions

The fault management and restoration problem are considered to be multi-objective optimization problem where various control parameters are included. These objective functions will be weighted and emerged into one objective function to make it easy and fast to solve the FMSR problem. The objective functions in this thesis are:

a- Maximizing the number of customers to be restored based on their priority model.

b- Maximizing the system profits.

c- Minimizing the operational cost of the DGs.

3.1.2 Control Variables

There are many control variables that can be controlled, three main control variables are to be considered in the thesis:

a- The status of the switch in the smart grid system.

b- The available power from DGs sources.

c- The amount of Load Curtailment and Shedding Loads.

3.1.3 Problem Constraints

There are many constraints that cannot be exceeded in order to have the optimum reconfiguration of the smart grid system. These constraints can be divided into two types [43]:

a- Technical Constraints

The restoration problem should be formulated considering technical constraints to maintain the smart grid network within the accepted limits, and the technical constraints that are included in this thesis are:

1- Bus voltages magnitude and angles.

2- Power flow rating of the line.

3- Maximum power limits of DGs and RES.

b- Management Constraints

This type of constraints is related to the agreement between the utilities and the customers to control and manage loads during peak times, which is known as the demand side management (DSM). In addition, EM constraints must be applied in the optimization problem since the system will trade energy with the ISO and customers. Figure 3.1 shows a summarized flowchart of the optimization process for the restoration optimization and the important parameters that need to be considered in solving the optimization problem.

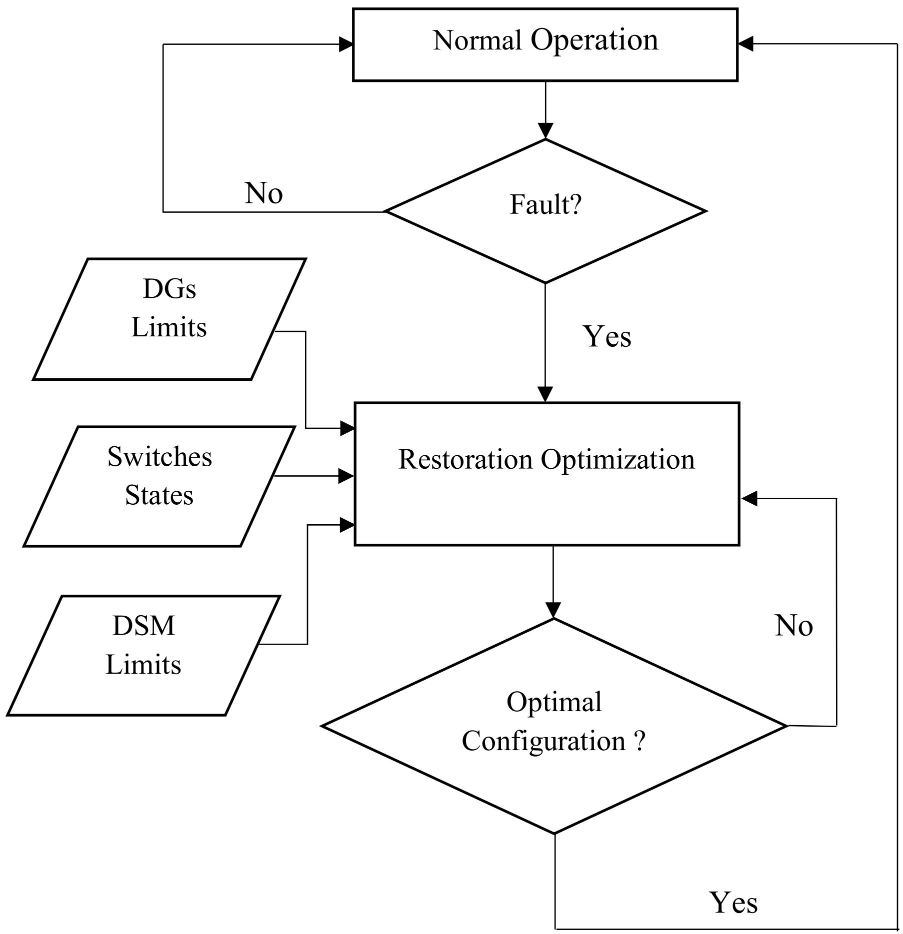

Figure 3.1 Restoration optimization flowchart

Figure 3.2 shows the details flowchart of the restoration optimization. There is a need for participating in the real time EM due to sudden faults occurrence and renewable power intermittence. After finding the optimal day ahead bids, the virtual microgrid operator will operate the system in the real time by starting to check for faults occurrence and the actual output power of renewable sources. Then, the virtual microgrid operator will run a real time internal market so that customers submit real time bids for adjustments. Based on real time settlements, the virtual microgrid operator decides whether it buys energy from the ISO to supply loads or sell energy to ISO to maximize its profits.

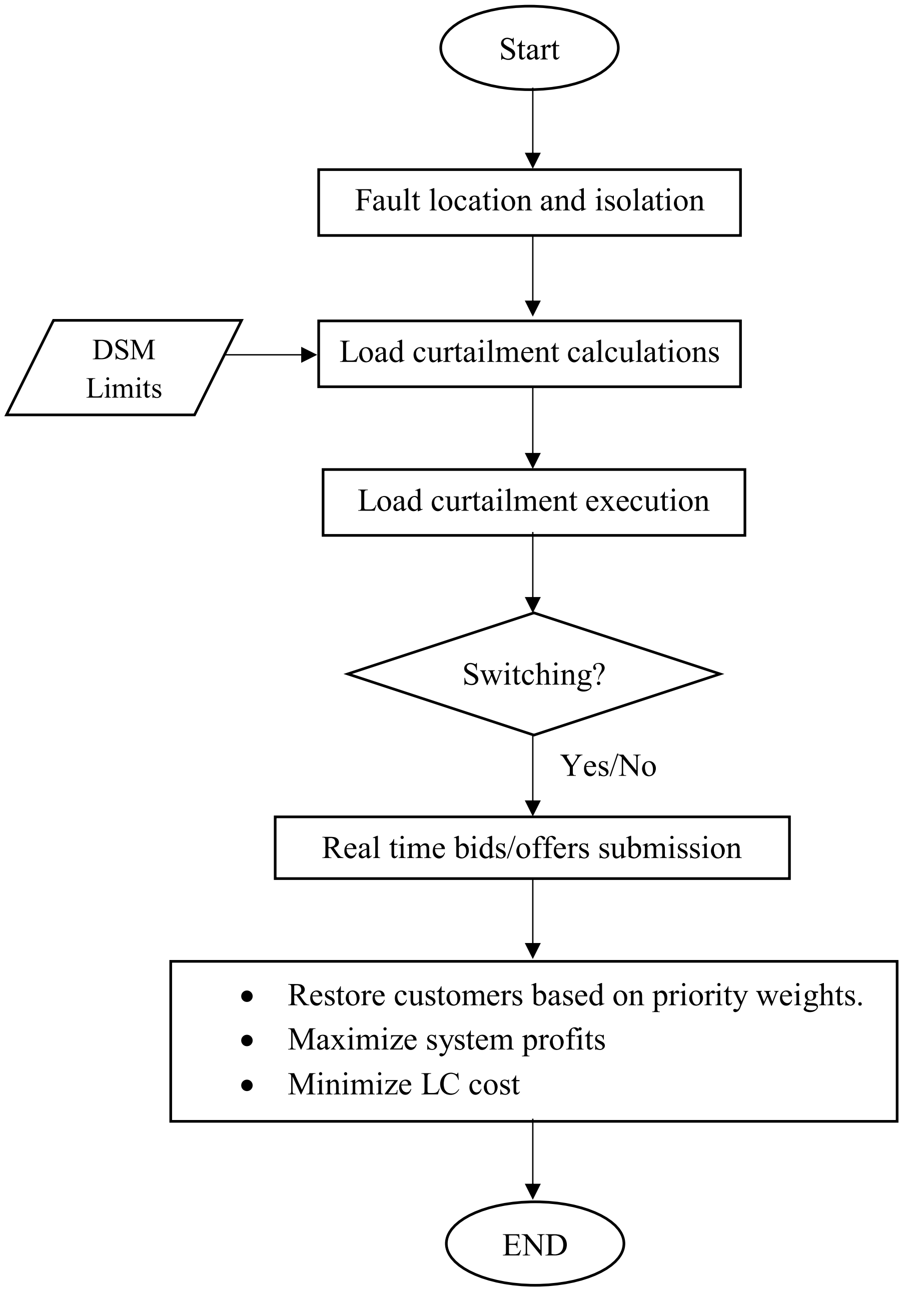

Figure 3.2 Detailed flowchart of the restoration process

Figure 3.3 shows timeline considered participating in EM, where the virtual microgrid operator starts with hourly bids calculated day ahead. Then, it will participate in the real time market to find the optimal bids/offers for the network where it takes 5-8 minutes to implement the restoration service.

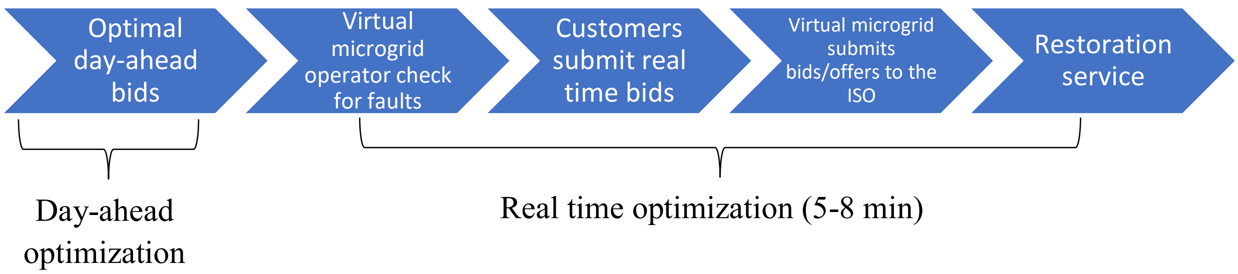

Figure 3.3 Timeline considered participating in EM

3.2 Methodology of the MILP Technique

The MILP technique that is used in this thesis is adopted from the reference [50] where it uses the nonlinear form of the following power equations:

$$P_i^{\alpha} = V_i^{\alpha} \sum_j^N \sum_{\beta}^{a-c} V_j^{\beta} (G_{ij}^{\alpha\beta} cos\theta_{ij}^{\alpha\beta} + B_{ij}^{\alpha\beta} sin\theta_{ij}^{\alpha\beta}) \quad (3.1)$$

$$Q_i^{\alpha} = V_i^{\alpha} \sum_j^N \sum_{\beta}^{a-c} V_j^{\beta} (G_{ij}^{\alpha\beta} sin\theta_{ij}^{\alpha\beta} - B_{ij}^{\alpha\beta} cos\theta_{ij}^{\alpha\beta}) \quad (3.2)$$

To linearize these equations, two assumptions are used:

1- The angle difference between connected buses are small and the trigonometric functions are linearized around 0, -2π/3, and 2π/3.

2- In normal operation conditions, the voltage magnitudes are all close to 1.

From the above assumptions, equations (3.1) and (3.2) can be linearized into:

$$\begin{bmatrix} P^A \\ P^B \\ P^C \\ Q^A \\ Q^B \\ Q^C \end{bmatrix} = \begin{bmatrix} J_{PV}^{AA} & J_{PV}^{AB} & J_{PV}^{AC} & J_{P\theta}^{AA} & J_{P\theta}^{AB} & J_{P\theta}^{AC} \\ J_{PV}^{BA} & J_{PV}^{BB} & J_{PV}^{BC} & J_{P\theta}^{BA} & J_{P\theta}^{BB} & J_{P\theta}^{BC} \\ J_{PV}^{CA} & J_{PV}^{CB} & J_{PV}^{CC} & J_{P\theta}^{CA} & J_{P\theta}^{CB} & J_{P\theta}^{CC} \\ J_{QV}^{AA} & J_{QV}^{AB} & J_{QV}^{AC} & J_{Q\theta}^{AA} & J_{Q\theta}^{AB} & J_{Q\theta}^{AC} \\ J_{QV}^{BA} & J_{QV}^{BB} & J_{QV}^{BC} & J_{Q\theta}^{BA} & J_{Q\theta}^{BB} & J_{Q\theta}^{BC} \\ J_{QV}^{CA} & J_{QV}^{CB} & J_{QV}^{CC} & J_{Q\theta}^{CA} & J_{Q\theta}^{CB} & J_{Q\theta}^{CC} \end{bmatrix} \cdot \begin{bmatrix} V^A \\ V^B \\ V^C \\ \theta^A \\ \theta^B \\ \theta^C \end{bmatrix} \tag{3.3}$$

Where

P^α, Q^α are the active and reactive power of bus α.

V^α, θ^α are the voltage magnitude and phase angle of bus α.

$J_{PV}^{\alpha\beta}, J_{QV}^{\alpha\beta}$ are an N×N matrix that relates P at phase α to V at phase β and Q at phase α to V at phase β for all N number of buses in the system.

3.2.1 The General Form of MILP

The MIP approach has two types as explained in the literature, and the type that is used in this thesis is the MILP where it is easier and faster for solving problems like FMSR. It can be used as either a maximizing or a minimizing problem and have the general form of:

$$\mathrm{Z} = \max(\min)\mathrm{CX} \tag{3.4}$$

Subjected to

$$\sum \mathrm{AX} \leq \mathrm{B} \tag{3.5}$$

Where

$X = (x_1, x_2, x_3, \dots, x_n)$ are control variables or decision variables.

$C = (c_1, c_2, c_3, \dots, c_n)$ are objective coefficients.

$B = (b_1, b_2, b_3, \dots, b_n)$ are right-hand side values of the constraints.

$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{bmatrix}$ are constants values of the constraints.

3.2.2 Disjunction or Decision Constraints

It can be notice from (3.5) that the constraint also must be in a linear form to solve the objective function. However, there are different types and forms of constraints where they need to be modified into a linear form. One of the types is the disjunction or decision constraint. When the constrain is in the form of $AX \leq B$, the control variable r = 1 is applied. However, when the control variable r = 0, the constraint is relaxed and need to be modified. To model such constraint, a constant M must be added so that it can be controlled by the control variable c.

The form of the constraint become:

$$\sum AX - B \leq M(1 - r) \tag{3.6}$$

Where

r is the control variable

M is a constant assured to be always greater than $\sum AX - B$.

3.3 Mathematical Formulation of the Optimization Problem

As mention in section 3.2.1, the FMSR problem is a multi-objective problem. In this thesis, three objectives functions are considered where they combined in one objective function to be optimized, and they are listed as follows:

3.3.1 Maximizing Number of Customers

The first objective function is maximizing the restored number of customers based on priority weights, where it depends on time of occurrence of the fault and its location and it is given by:

$$\mathrm{Obj}_1 = \mathrm{Max} \sum_{i=1}^{N_L} (w_{i,t}^{priority} \cdot \rho_t) \tag{3.7}$$

Where

$w_{i,t}^{priority}$	The weight of priority for each load i at time of fault t.
ρ_t	A binary decision related to the customer restored at time of fault t.

3.3.2 System Profits/Operation Cost

The second objective can be either maximizing the system profits and it is given by:

$$\mathrm{Obj}_2 = \mathrm{Max}\ (\lambda_t^{RT} \cdot P_t^{RT}) \tag{3.8}$$

given that

$$P_t^{RT} = P_t^{Load} - P_t^{Conv} - P_t^{Ren} - P_t^{DA} \tag{3.9}$$

Where

λ_t^{RT}	Price of selling/buying from/to the ISO at time of fault t.
P_t^{RT}	The real-time loads at time of fault t.
P_t^{Load}	Total loads after reducing the accepted customer's bids at time of fault t.
P_t^{Conv}	Total output power of conventional generators at time of fault t.
P_t^{Ren}	Total output power of the renewable sources at time of fault t.
P_t^{DA}	The capacity of the Day-Ahead bids from/to the ISO at time of fault t.

It is obvious from (3.9) that if the value of the $\mathrm{P_t^{RT}} > 0$, then the system is going to buy energy from the ISO which means minimizing the objective function as a cost, but if the value of the $\mathrm{P_t^{RT}} < 0$, then the system is going to sell energy to the ISO, hence the objective function become maximizing the profit.

3.3.3 Curtailment Cost

The third objective of this thesis is to minimize the cost of curtailment. Since each customer is participating in a DSM programs, the system is paying the customers for the amount of curtailed energy as a compensation, and it is given by:

$$\mathrm{Obj_3} = \mathrm{Min}(\,\lambda_t^{DR} \cdot \mathrm{P_t^{LC}}) \tag{3.10}$$

Where

λ_t^{DR} Price paying to the customers for participating in DSM.

P_t^{LC} Amount of curtailed energy from the customer side.

3.3.4 Overall Objective Function

The multi-objectives function of this thesis is to solve the restoration problem based on the three objective functions above. They need to be combined in one objective function so that the system works optimally during faults while it participates in the EM. Each objective function must be converted to a per unit scale. The general objective function of the FMSR problem can be expressed as:

$$\text{Max} \quad (\mathrm{w}^{\mathrm{Obj}_1} \cdot \mathrm{Obj}_1) + (\mathrm{w}^{\mathrm{Obj}_2} \cdot \mathrm{Obj}_2) + (\mathrm{w}^{\mathrm{Obj}_3} \cdot \mathrm{Obj}_3) \quad (3.11)$$

Where

w^{Obj_1} Weight of the first objective function related to number of customers restored.

w^{Obj_2} Weight of the second objective function related to the system profits/costs.

w^{Obj_3} The weight of the third objective function related to the LC cost.

These weights depend on the users or utilities decision where it vary the importance between maximizing the number of customers restored, participating in the EM or minimizing the curtailment cost.

3.4 Problem Constraints Formulation

As mentioned previously, the restoration problem must be solved within limits of constraints with different types. In the following sections, each constrain is formulated in a linearized form so that the proposed MILP technique work without exceeding these constraints.

3.4.1 Renewable Resources

$$0 \leq \mathrm{PV}_{\mathrm{t}}^{\alpha} \leq \mathrm{PV}^{\mathrm{Max}} \tag{3.12}$$

$$0 \leq \mathrm{W}_{\mathrm{t}}^{\alpha} \leq \mathrm{W}^{\mathrm{Max}} \tag{3.13}$$

Where

PV_t^{α}: The output power of the solar source of phase α at time of fault t.

PV^{Max}: The maximum power of the solar source.

W_t^{α}: The output power of the wind farm of phase α at time of fault t.

W^{Max}: The maximum power of the wind farm.

3.4.2 Conventional Generators

$$\mathrm{P}^{\mathrm{Conv,Min}} \leq \mathrm{P}_{\mathrm{i,t}}^{\mathrm{Conv}} \leq \mathrm{P}^{\mathrm{Conv,Max}} \tag{3.14}$$

$$\mathrm{Q}^{\mathrm{Conv,Min}} \leq \mathrm{Q}_{\mathrm{i,t}}^{\mathrm{Conv}} \leq \mathrm{Q}^{\mathrm{Conv,Max}} \tag{3.15}$$

$$-\mathrm{Ramp} \leq \mathrm{P}_{\mathrm{i,t}}^{\mathrm{Conv}}\mathrm{P}_{\mathrm{i,t-1}}^{\mathrm{Conv}} \leq \mathrm{Ramp} \tag{3.16}$$

Where

$P_{i,t}^{Conv}$: The active power output of the conventional generator I at time t.

$P^{Conv,Min}$: The minimum active output power of the conventional generator.

$P^{Conv,Max}$: The maximum active output power of the conventional generator.

$Q_{i,t}^{Conv}$: The reactive power output of the conventional generator I at time t.

$Q^{Conv,Min}$: The minimum reactive output power of the conventional generator.

$Q^{Conv,Max}$: The maximum reactive output power of the conventional generator.

$Ramp$: The generator ramping rate.

3.4.3 Demand Response

$$P_{i,t}^{load} = \sum_{i=1}^{N_L}(L_{i,t}) - P_{i,t}^{LC} \tag{3.17}$$

$$P_{t}^{LC} = \sum_{i=1}^{N_{CL}}(Y_{i,t} \cdot P_{i,t}^{LC}) \tag{3.18}$$

$$P_{i,t}^{LC} \leq P_{i}^{LC,Max} \tag{3.19}$$

Where

$L_{i,t}$: The total demand of load i at time of fault t.

$P_{i,t}^{LC}$: The curtailed amount of load i at time of fault t.

$Y_{i,t}$: Binary decision variable specifies the acceptance of bids from customer i at time t.

$P_i^{LC,Max}$: The maximum allowed amount of accepted amount of load reduction.

3.4.4 System Constraints

- **Un-Switchable Branches:**

$$P_t^{Conv} + W_t + PV_t + P_t^{RT} = P^{Load} + P^{Loss} \tag{3.20}$$

$$P_{ij}^{\alpha} \approx \frac{r_{ij}^{\alpha} \cdot x_{ij}^{\alpha}}{\left({r_{ij}^{\alpha}}^2 + {x_{ij}^{\alpha}}^2\right) \cdot x_{ij}^{\alpha}} \cdot \left(V_i^{\alpha} - V_j^{\alpha}\right) + \frac{{x_{ij}^{\alpha}}^2}{\left({r_{ij}^{\alpha}}^2 + {x_{ij}^{\alpha}}^2\right) \cdot x_{ij}^{\alpha}} \cdot \left(\theta_i^{\alpha} - \theta_j^{\alpha}\right) \tag{3.21}$$

$$Q_{ij}^{\alpha} \approx \frac{-r_{ij}^{\alpha} \cdot x_{ij}^{\alpha}}{\left({r_{ij}^{\alpha}}^2 + {x_{ij}^{\alpha}}^2\right) \cdot x_{ij}^{\alpha}} \cdot \left(\theta_i^{\alpha} - \theta_j^{\alpha}\right) + \frac{{x_{ij}^{\alpha}}^2}{\left({r_{ij}^{\alpha}}^2 + {x_{ij}^{\alpha}}^2\right) \cdot x_{ij}^{\alpha}} \cdot \left(V_i^{\alpha} - V_j^{\alpha}\right) \tag{3.22}$$

$$V_i^{Min} \leq V_i^{\alpha} \leq V_i^{Max} \tag{3.23}$$

$$\theta_i^{Min} \leq \theta_i^{\alpha} \leq \theta_i^{Max} \tag{3.24}$$

$$\left|P_{ij}^{\alpha}\right| \leq P_{ij}^{Max} \tag{3.25}$$

$$\left|Q_{ij}^{\alpha}\right| \leq Q_{ij}^{Max} \tag{3.26}$$

$$|SL_t^{\alpha}| \leq SL^{Max} \tag{3.27}$$

Where

P_{ij}^{α}: The transferred active power on a line from bus i to bus j in a phase α.

Q_{ij}^{α}: The transferred reactive power on a line from bus i to bus j in a phase α.

r_{ij}^{α}: Resistance line between bus i and bus j in phase α.

x_{ij}^{α}: Reactance line between bus i and bus j in phase α.

V_{i}^{α}: The voltage magnitude at but i and phase α.

θ_{i}^{α}: The voltage angle at but i and phase α.

SL_{t}^{α}: The transferred power between the VPP and ISO at time t and phase α.

- **Switchable Branches:**
  - Closed branch ($u_{ij} = 1$)

$$-M_{ij}^{P}\left(1-u_{ij}\right) \leq P_{ij}^{\alpha} - k_1 \cdot \left(V_i^{\alpha} - V_j^{\alpha}\right) - k_2\left(\theta_i^{\alpha} - \theta_j^{\alpha}\right) \leq M_{ij}^{P}(1-u_{ij}) \tag{3.28}$$

$$-M_{ij}^{Q}\left(1-u_{ij}\right) \leq Q_{ij}^{\alpha} - k_1 \cdot \left(\theta_i^{\alpha} - \theta_j^{\alpha}\right) - k_2\left(V_i^{\alpha} - V_j^{\alpha}\right) \leq M_{ij}^{Q}(1-u_{ij}) \tag{3.29}$$

  - Opened branch ($u_{ij} = 0$)

$$-M_{ij}^{V} \cdot u_{ij} \leq V_{ij}^{\alpha} \leq M_{ij}^{V} \cdot u_{ij} \tag{3.30}$$

$$-M_{ij}^{\theta} \cdot u_{ij} \leq \theta_{ij}^{\alpha} \leq M_{ij}^{\theta} \cdot u_{ij} \tag{3.31}$$

$$k_1 = \frac{r_{ij}^{\alpha} \cdot x_{ij}^{\alpha}}{\left(r_{ij}^{\alpha^2} + x_{ij}^{\alpha^2}\right) \cdot x_{ij}^{\alpha}} \tag{3.32}$$

$$k_2 = \frac{x_{ij}^{\alpha^2}}{\left(r_{ij}^{\alpha^2} + x_{ij}^{\alpha^2}\right) \cdot x_{ij}^{\alpha}} \tag{3.33}$$

Where

M_{ij}^{P}: A disjunctive constant that must be always larger than $|P_{ij}^{\alpha} - k_1 \cdot \left(V_i^{\alpha} - V_j^{\alpha}\right) - k_2\left(\theta_i^{\alpha} - \theta_j^{\alpha}\right)|$.

M_{ij}^{Q}: A disjunctive constant that must be always larger than $|Q_{ij}^{\alpha} - k_1 \cdot \left(\theta_i^{\alpha} - \theta_j^{\alpha}\right) - k_2\left(V_i^{\alpha} - V_j^{\alpha}\right)|$.

M_{ij}^{V}: A disjunctive constant that must be always larger than $|V_{ij}^{\alpha}|$.

M_{ij}^{θ}: A disjunctive constant that must be always larger than $|\theta_{ij}^{\alpha}|$.

3.4.5 Energy Market Constraints

$$C_t^{Conv} = \sum_{i=1}^{N_G} (a_i + b_i \cdot P_{i,t}^{Conv}) \tag{3.34}$$

$$\mathrm{P_t^{RT}} = SL_t^a + SL_t^b + SL_t^c \tag{3.35}$$

$$0 \leq C_t^{Conv} \leq C^{Conv,Max} \tag{3.36}$$

Where

a_i, b_i: The cost coefficients of the conventional generator i.

3.4.6 Radiality Constraints

$$\sum_{ij=1}^{N_l^{Loop}} u_{ij} \leq N_i^{Loop} - 1 \tag{3.37}$$

where

u_{ij}: The branch switch state.

N_l^{Loop}: Number of branches in loop l.

3.5 Proposed System Model

3.5.1 IEEE 13-Bus Test System

The system that was implemented and tested to apply the proposed optimization problem is the IEEE 13 bus test system as presented in Figure 3.4 [49], where Figure 3.5 shows the single line diagram of each phase of the system. For more simplicity, the number of nodes are adopted as shown in the Appendix A.2, and all the voltage regulators and transformers are ignored; so, node 634 and node 692 are ignored.

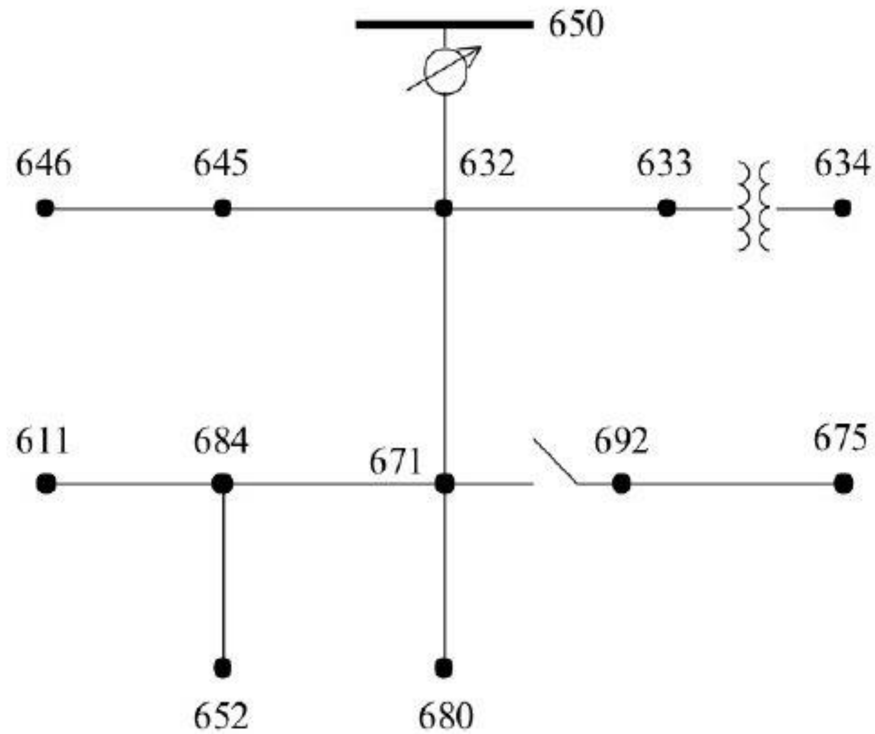

Figure 3.4 IEEE 13 bus test system [49]

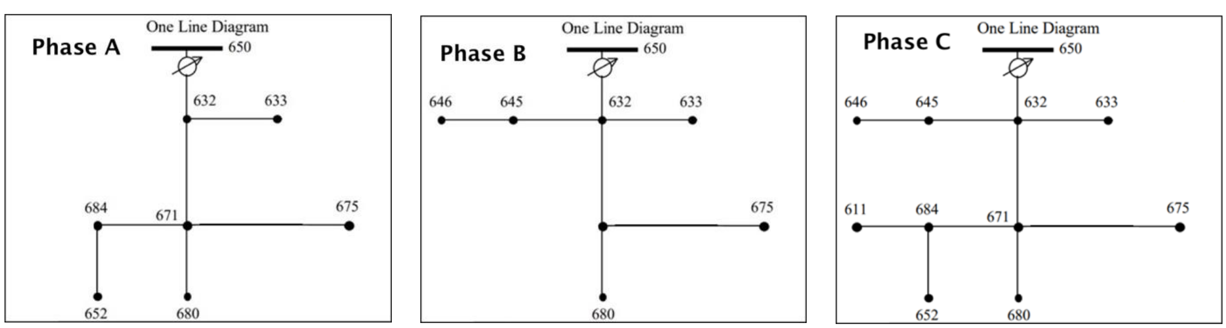

Figure 3.5 Single line diagram per phase

3.5.2 DG Sources and Load Types

Reference [49] shows the details of the line data and loading conditions of the IEEE 13 bus test system. However, the system is modified by adding two types of loads: commercial and residential loads. In addition, renewable energy sources were added at specific buses in the system. Table 3.1 shows the modified busses with the used type of generator and their output power capacity and Table 3.2 shows the modified busses with the type of load.

Table 3.1 Modified buses with type of generator

Bus	Generator Type	Phase A (KW)	Phase B (KW)	Phase C (KW)
611	Conventional	-	-	1000
671	Conventional	1000	-	-
675	Solar	1000	1000	1000
680	Conventional	-	1000	-
684	Wind	600	600	600
Total (KW)		**2600**	**2600**	**2600**

Table 3.2 Modified buses with type of load

Bus	Commercial Load	Residential Load
611	-	Yes
633	-	Yes
671	Yes	-
675	Yes	-
680	-	Yes

CHAPTER 4

RESULTS AND DISCUSSIONS

The verification of the proposed MILP approach for solving the FMSR problem is going to be presented in this chapter. Different case studies examined the proposed optimization where it is applied using CVX software. CVX is a Matlab based modeling system where it is used to optimize different types of mathematical formulations. It turns Matlab into a modeling language where it solves the objective functions and applies the constraints by using the standard Matlab expression. However, to optimize the problem as a linear problem, a tool called Gurobi must be installed in the CVX software. In the following sections, three case studies are presented of the FMSR problem showing different fault location and different level of restoration. Each case represents a feature of the proposed virtual microgrid model. All the faults of the cases are assumed to be occurred at 11 am. Although it must take part of seconds to restore the system, however, optimizing the restoration problem is shown as a 1 hour period in the results to make it clear to read.

4.1 Case 0: Normal Operation

To make sure that the proposed FMSR technique is working fine, we need to see how the system behave during normal operation condition where no faults are occurred. As mentioned in chapter 3, the system is the IEEE 13 bus test system with three conventional generators, a solar source and a wind farm. Two types of loads are in the system, commercial and residential. In addition, bus 2 assumed to be connected to the ISO where the energy is traded between the system and the ISO.

After running the system without any faults, the following results has been recorded and analyzed for 24 hours. The load demand of the system is shown in Figure 4.1 where we can see that between 7:00 am and 19:00 pm is the highest rate of loads. In addition, since the system is participating in the EM, a Day-Ahead Bids are sold from the system to the ISO in order to maximize the profit of the system and it is shown in Figure 4.2. We can notice that that the system is selling energy to ISO between 7:00 am and 19:00 pm at the same period of the higher rate of loads.

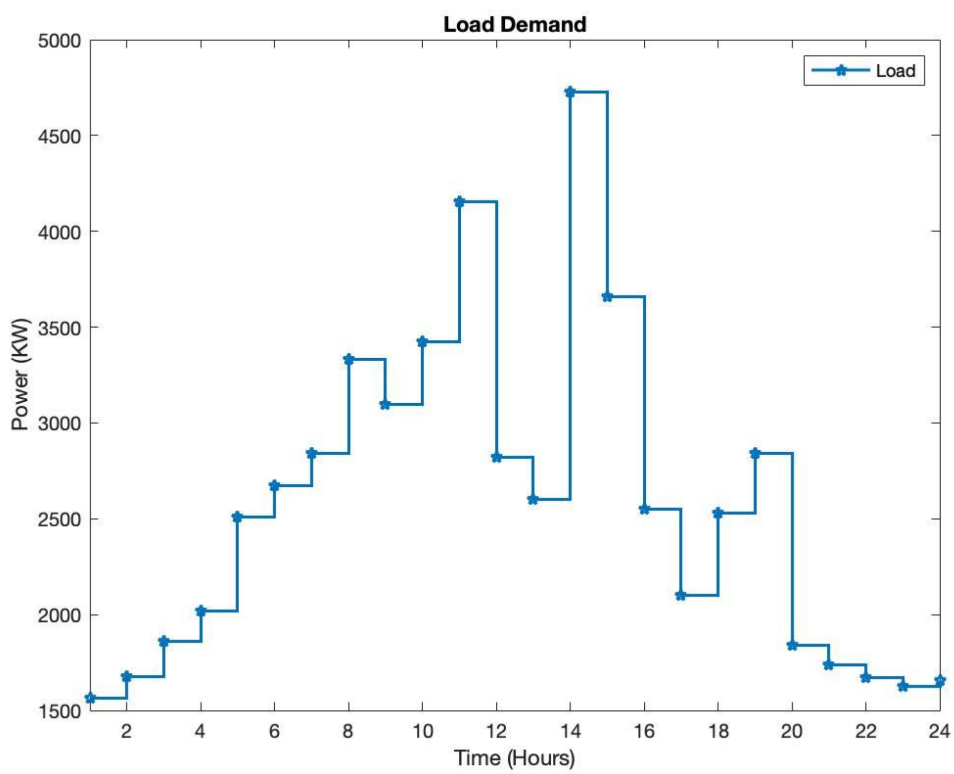

Figure 4.1 Load demand of the system for 24 hours

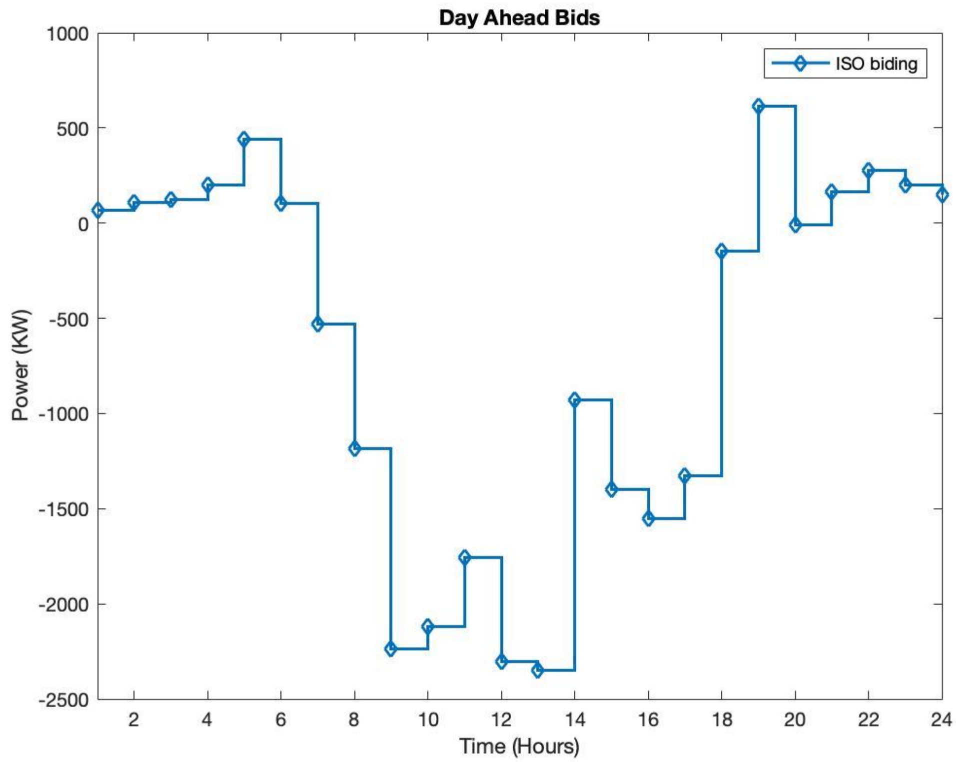

Figure 4.2 Day ahead bids between the system and ISO

Figure 4.3 shows a comparison between the generated energy from the conventional and renewable sources and the load demand of the system, and it is clear that the total generated energy is equal to the total load demand of the system. The prices of trading energy in the EM are shown in Figure 4.4, where it consists with the price of trading energy from ISO, price of generating energy from the conventional generators, price of compensation to customers participating in the DSM, and the price of energy from the VPP.

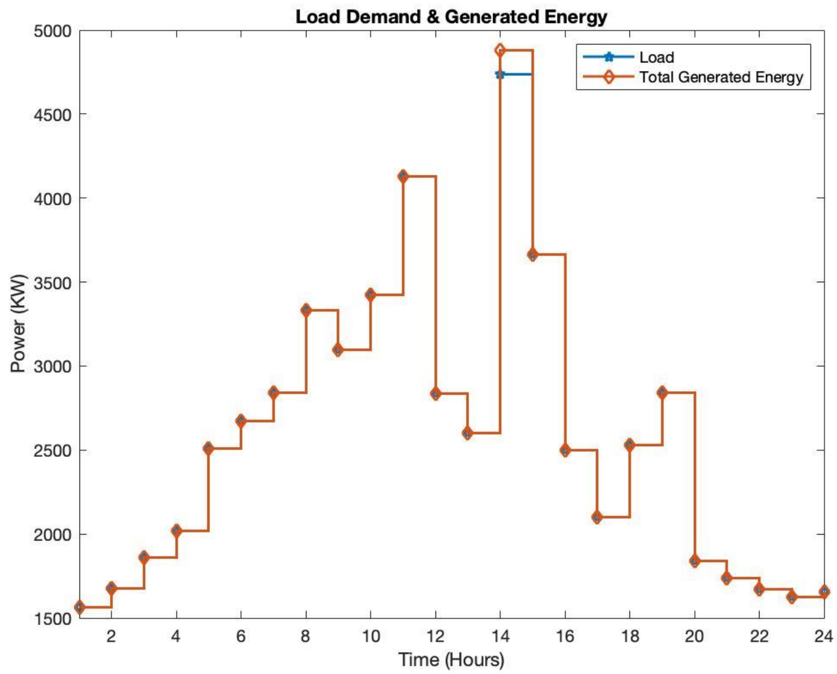

Figure 4.3 Comparison between generated energy and the load demand.

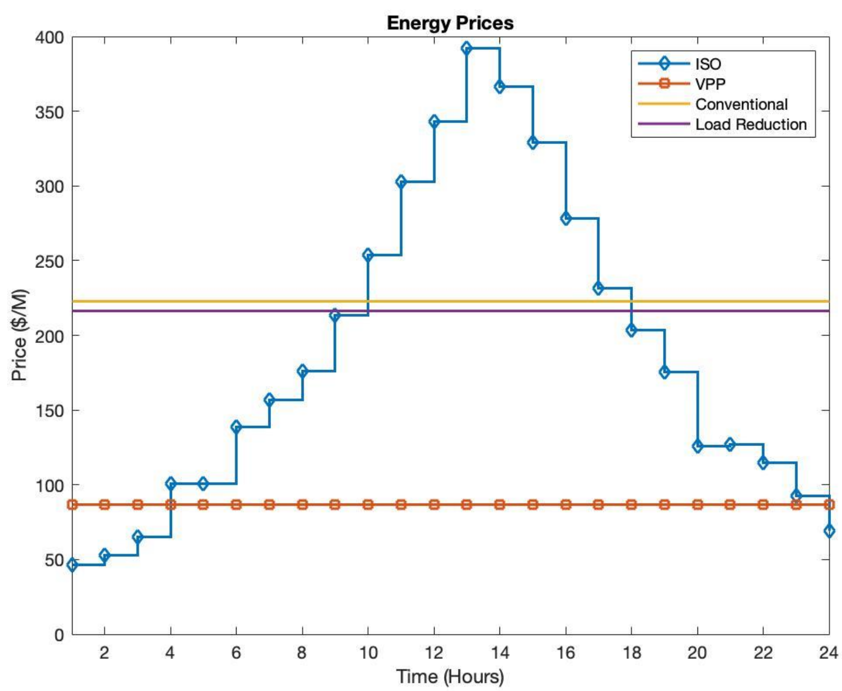

Figure 4.4 Prices of the EM

4.2 Case 1: Fault at Line L_{4-5}

To test the proposed approach during fault, case 1 is presented where a fault is occurred on line L_{4-5} as shown in Figure 4.5. Because of the design of the system, only the customers in bus 5 are affected where they are sheded and cannot be restored, the load demand after losing the customers in bus 5 and after participating the others in the DSM program is shown in Figure 4.6. It can be noticed between 11:00 am and 12:00 pm, where the fault occurred, that the load demand decreased from around 4300 KW (normal operation) into 3500 KW (case 1). The results show that the accepted amount of curtailed power is 297 KW which means that almost 500 KW was not restored because the lost customers at bus 5.

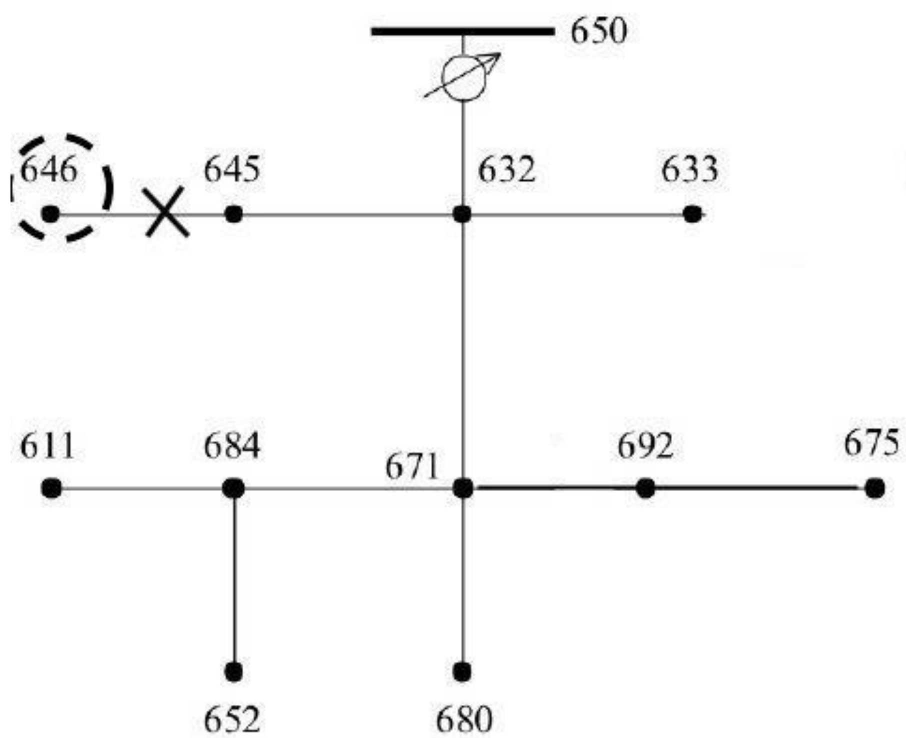

Figure 4.5 Case 1 with fault at line L_{4-5}

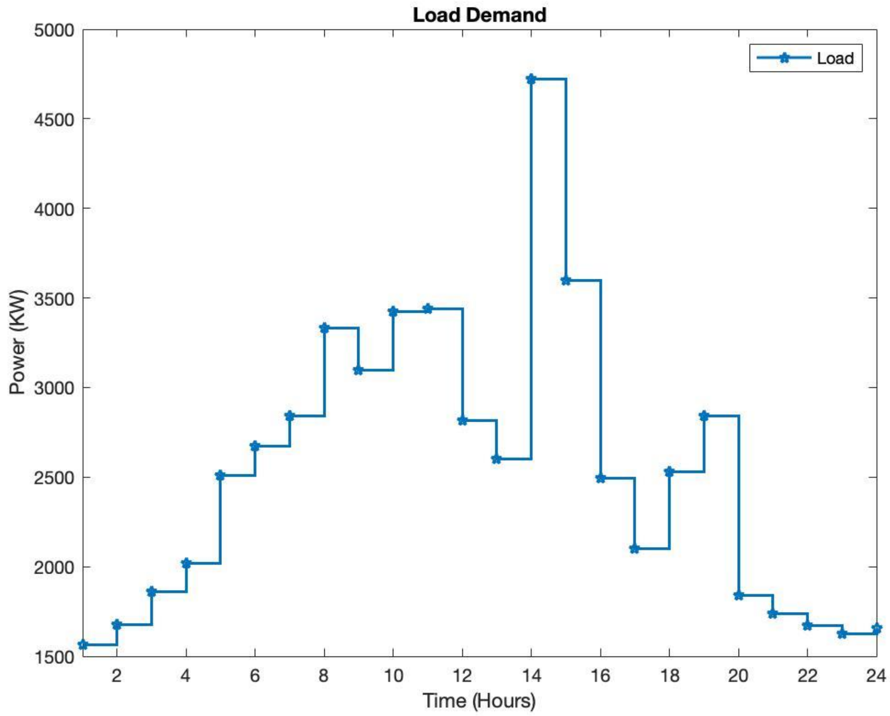

Figure 4.6 Load demand with fault at line L_{4-5}

After running the load flow of the system with the optimization approach, the optimal configuration shows that the system is selling energy to the ISO with an amount of 2421 KW as in Figure 4.7. This amount is generated from the DG sources which is comprise of an amount of around 400 KW of the day-ahead bids for the customers lost at bus 5 which the system generates it in order to compensate the cost of the day ahead bids. In addition, the extra-generated power (about 2020 KW) from the DG sources is for maximizing the system profits.

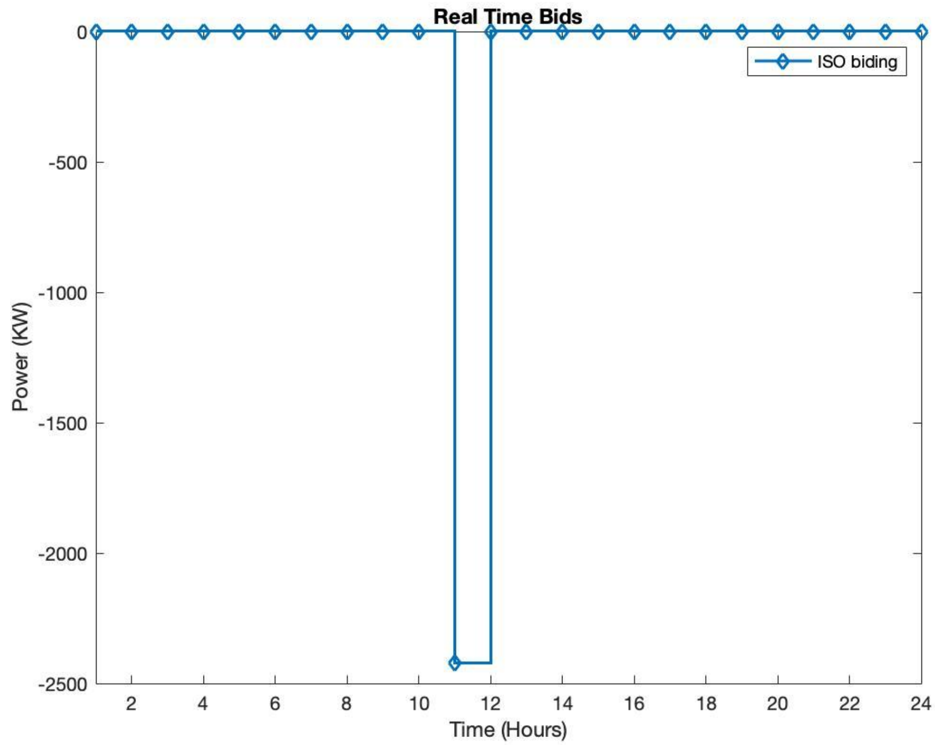

Figure 4.7 Real time bidding sold to ISO

Figure 4.8 shows the details of the optimal configuration for a 24 hour, it can be noticed at hour 11:00 am that the summation of the total generated energy and the bidding sold to the ISO is almost equal to the total load demand. The difference between the value Load and Load without fault is the amount of the curtailed energy and the lost loads at bus 5. The resulted voltage magnitude values of the restored system compared to the normal operation results is shown in Figure 4.9. It is cleared that the system is working within the accepted limits of the voltage magnitude.

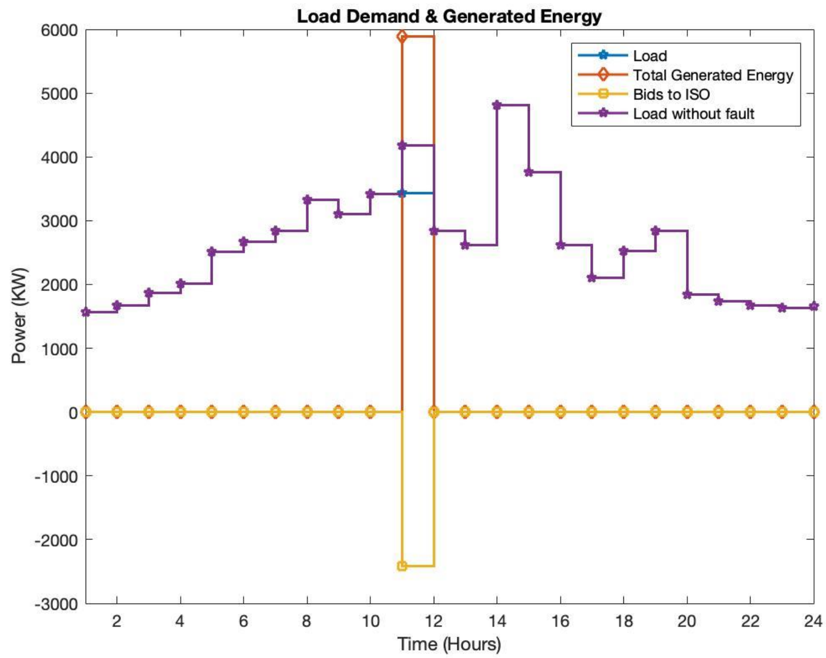

Figure 4.8 Optimal results of the system of case 1

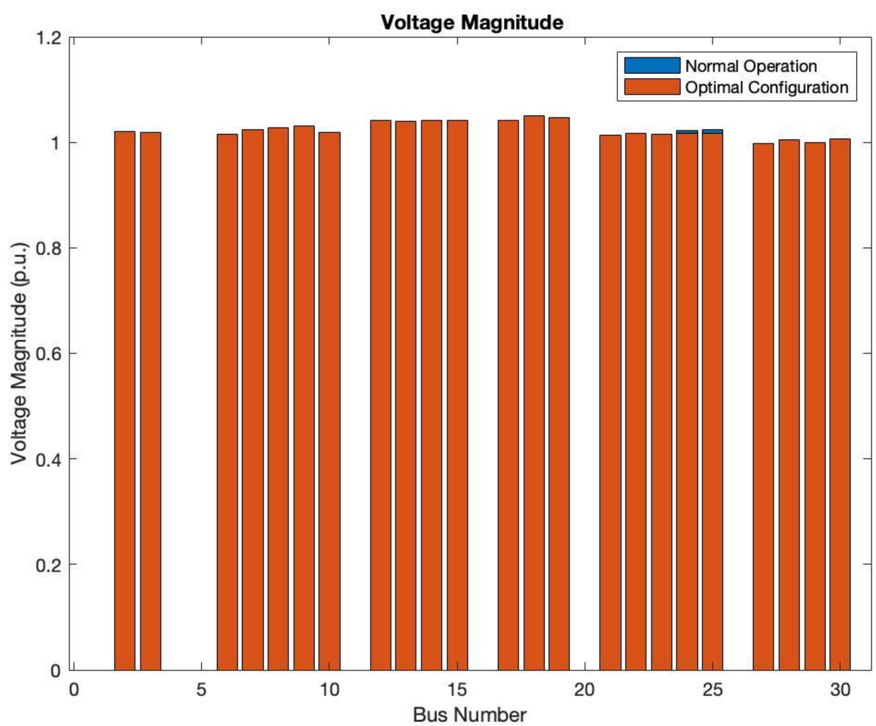

Figure 4.9 Voltage magnitude of case 1

The results of solving the objective function of this thesis is summarized in Table 4.1. Only 2 customers out of a total 13 customers are lost and the system succeed in restoring as much as it possible to the system and maximize the its profits. Table 4.2 shows a comparison of case 1 with when the system is participating in EM and without participating in EM where it validates the results obtained from the proposed optimization in both conditions.

Table 4.1 Results of the optimized objective function in case 1

Number of Customers Restored	11 Customers
Curtailed Cost ($)	-14.6187
Profit ($)	+190.6359
Total Profit ($)	+176.0172

Table 4.2 Optimization with EM vs. optimization without EM in case 1

	Optimization with EM	**Optimization Without EM**
Total Loads (KW)	4181	4181
Loads After Fault (KW)	3437	3733
Bids (KW)	2421 Selling	0
Generated (KW)	5892	3863

4.3 Case 2: Fault at Line L_{1-10}

For the second case, the line L_{1-10} is faulted where a conventional generator and customers at bus 1 are lost which make it harder to be optimized than case 1 as shown in Figure 4.10. The amount of the lost loads at bus 1 is about 450 KW and the accepted curtailed power is 296 KW. The resulted load demand after the fault occurred and after subtracting the amount of the curtailed power is shown in Figure 4.11.

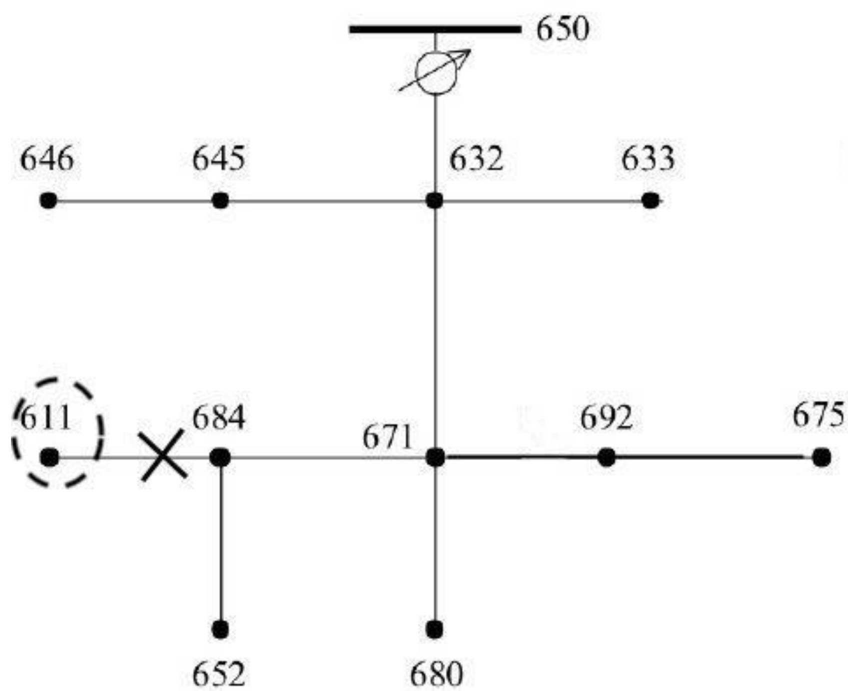

Figure 4.10 Case 2 with fault at line L_{1-10}

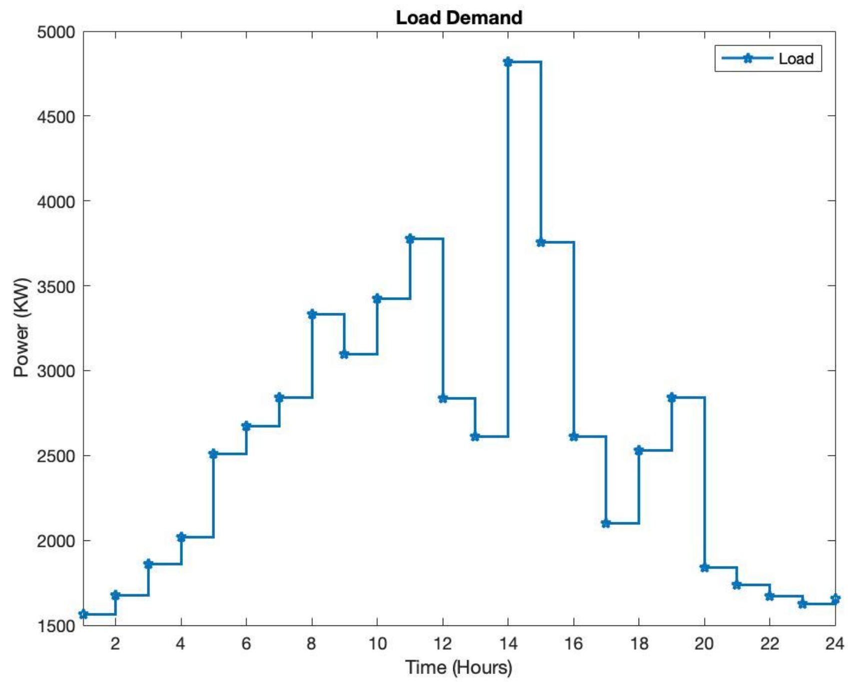

Figure 4.11 Load demand with fault at line L_{1-10}

By logical analysis, there is a need for a replacement of the energy lost from losing the conventional generator in order to restore as much customers to the system. The results of the optimal configuration of the system validate the logical analysis where energy from the ISO is purchased and 12 customers out of 13 are restored. Figure 4.12 shows the bids that purchased from ISO with an amount of 2707 KW.

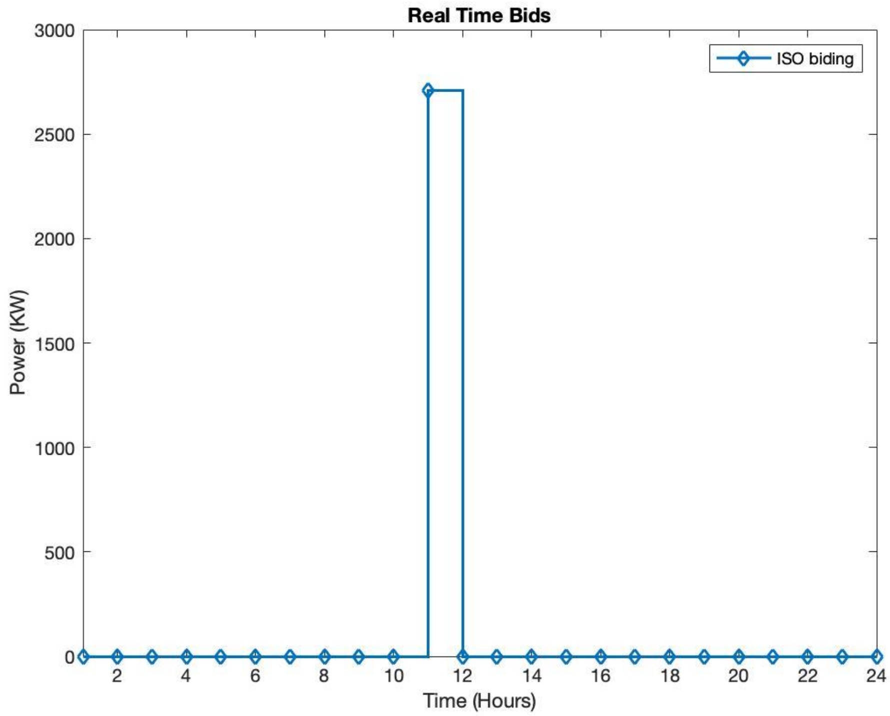

Figure 4.12 Real time bidding purchased from ISO

The details of the optimal results of the system for case 2 are shown in Figure 4.13. To verify the results, we can see that summation of the generated energy and the bids purchased from the ISO is equal to the total load at the time of fault. The resulted voltage magnitude values of the restored system compared to the normal operation results is shown in Figure 4.14. Table 4.3 shows the comparison when the system is participating in EM and when it is not, it can be seen that the system generates more energy when it is not participating in the EM.

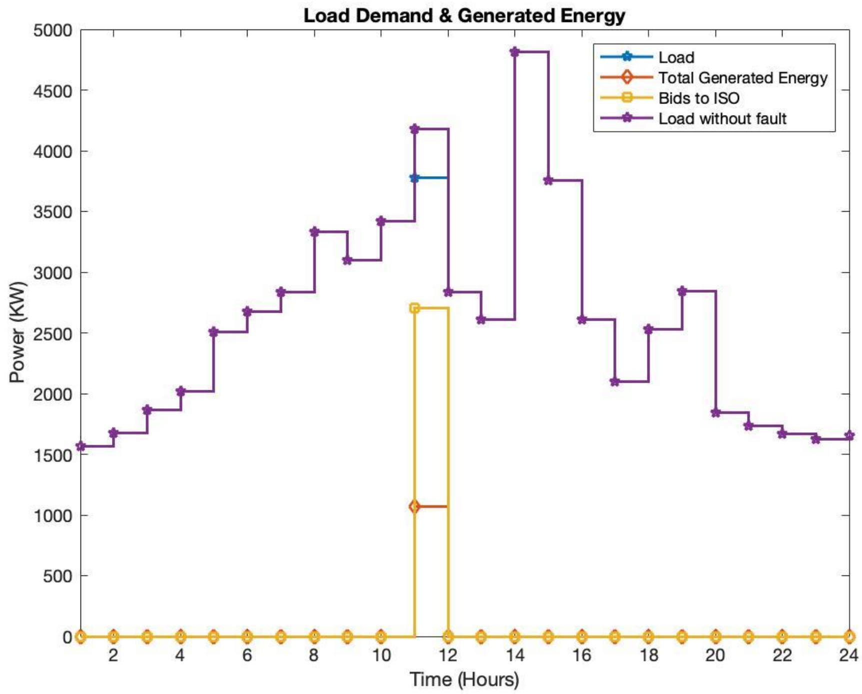

Figure 4.13 Optimal results of the system of case 2

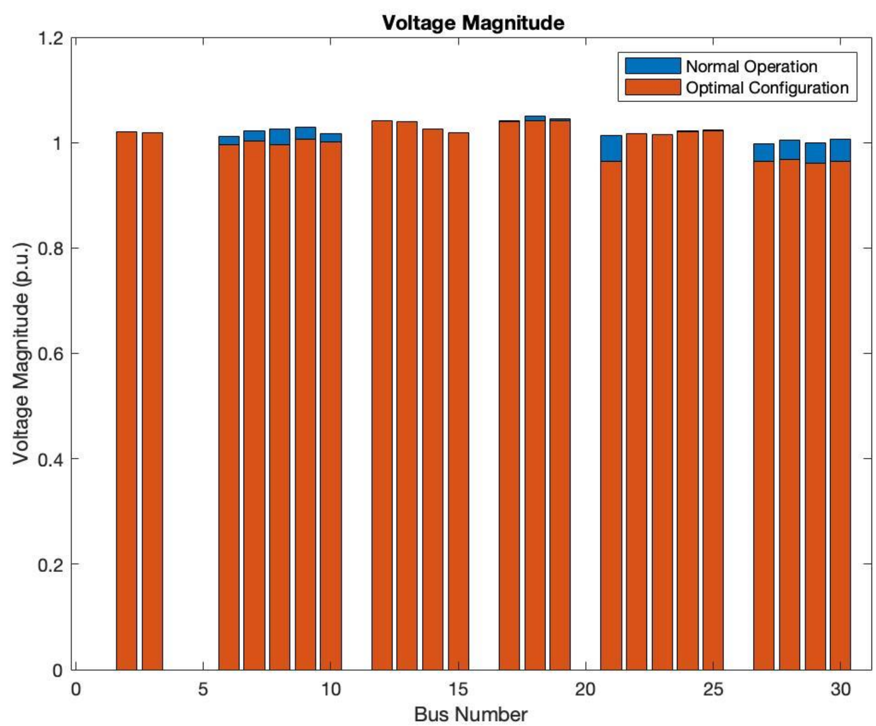

Figure 4.14 Voltage magnitude of case 2

Table 4.3 Optimization with EM vs. optimization without EM in case 2

	Optimization with EM	Without EM
Total Loads (KW)	4181	4181
Loads After Fault (KW)	3774	3733
Bids (KW)	2707 Buying	0
Generated (KW)	1067	3863

In Table 4.4, the results of optimizing the objective function of this thesis is presented and showing how much does it cost for the purchased energy. The energy is generated from both the conventional and the renewable sources, Figure 4.15 and Figure 4.16 show how the renewable resources is behaving and it can be noticed that at the time of the fault, almost the maximum capacity is generated when the system is not participating in EM.

Table 4.4 Results of the optimized objective function in case 2

Number of Customers Restored	12
Curtailed Cost ($)	-14.1622
Cost/PF ($)	-213.2048
Total Cost/PF ($)	-227.367

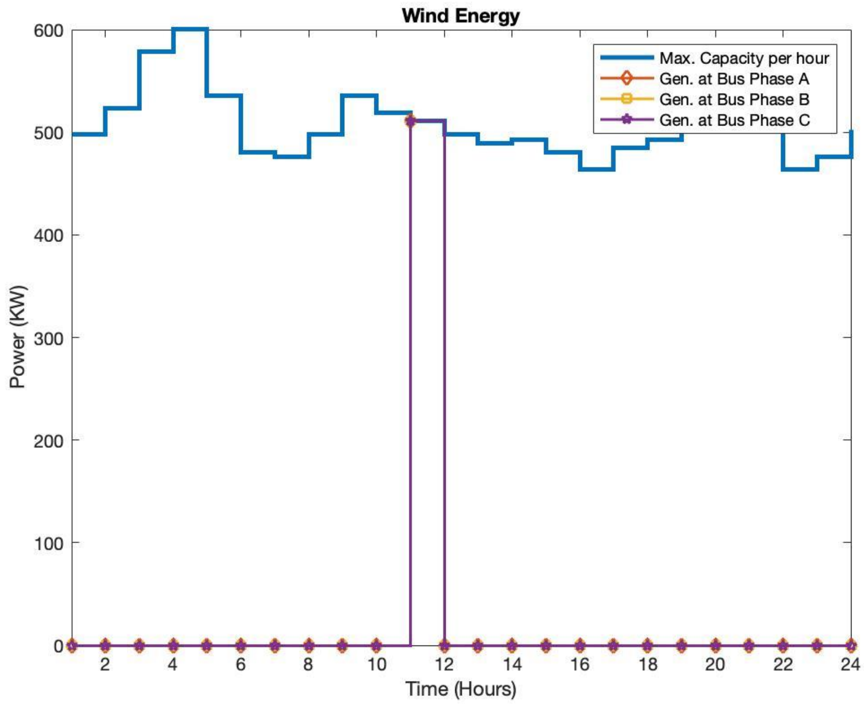

Figure 4.15 Output energy of the wind farm

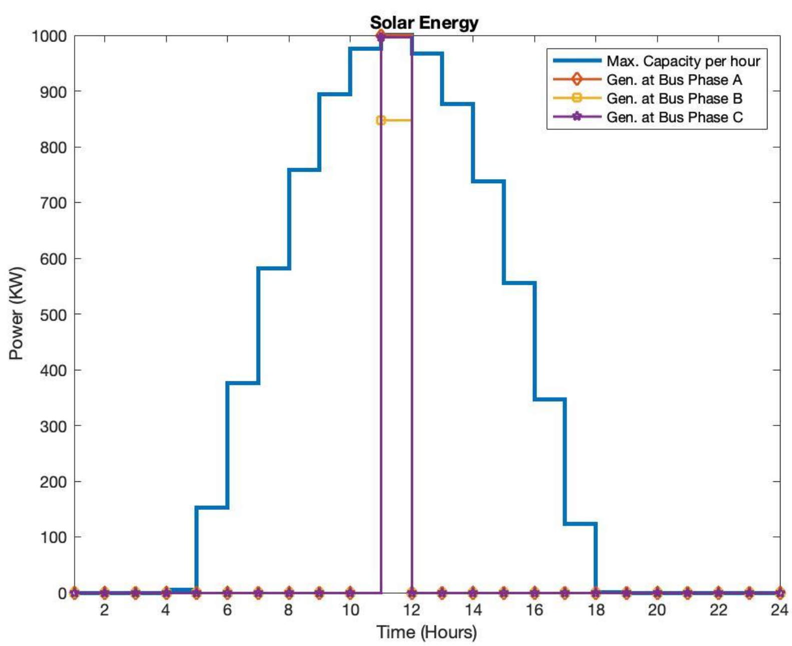

Figure 4.16 Output energy of the solar source

4.4 Case 3: Fault at Line L_{2-7}

This case is much more complicated than the previous cases. A fault is applied on line L_{2-7} as shown in Figure 4.17. The fault separate the upper part of the system than the lower. It shows the main idea of the proposed virtual microgrid where it will work optimally during islanded mode along with participating in the EM. Only loads are located in the upper part of the system, and no generations are there to supply the loads. On the other hand, in the lower part of the system is the conventional generators and the renewable sources.

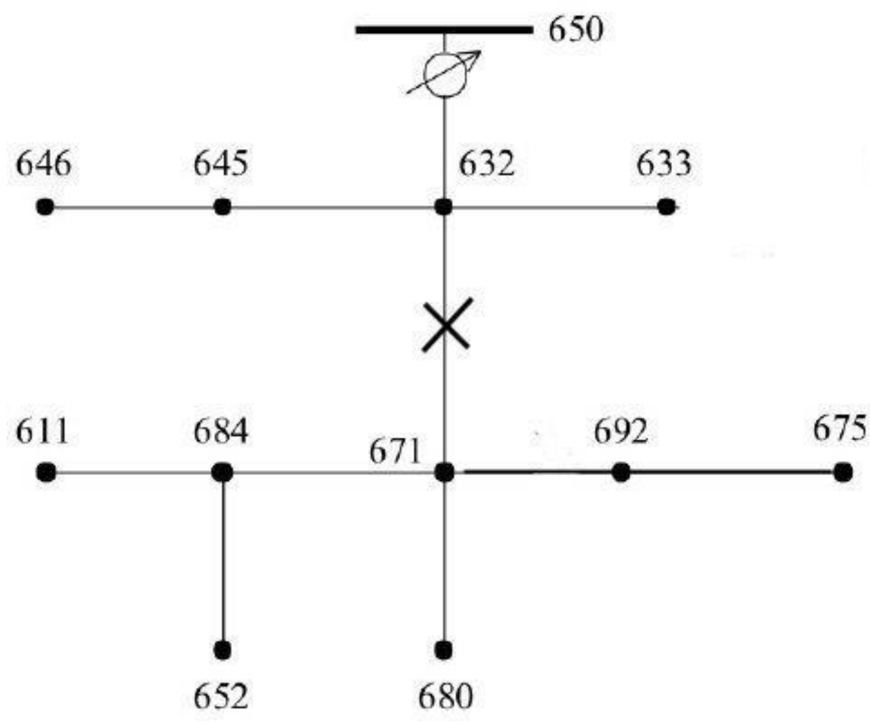

Figure 4.17 Case 3 with fault at line L_{2-7}

Since the system is participating in the EM and has the ability of working in islanding mode, each subsection of the system will run and supplied the loads from different sources of energy. Because of the participating in EM, the upper part of the system will provide the loads by buying energy from ISO as shown in Figure 4.18 with an amount of 775.4 KW, not participating in EM will leads to lose all the customers in the upper part of the system.

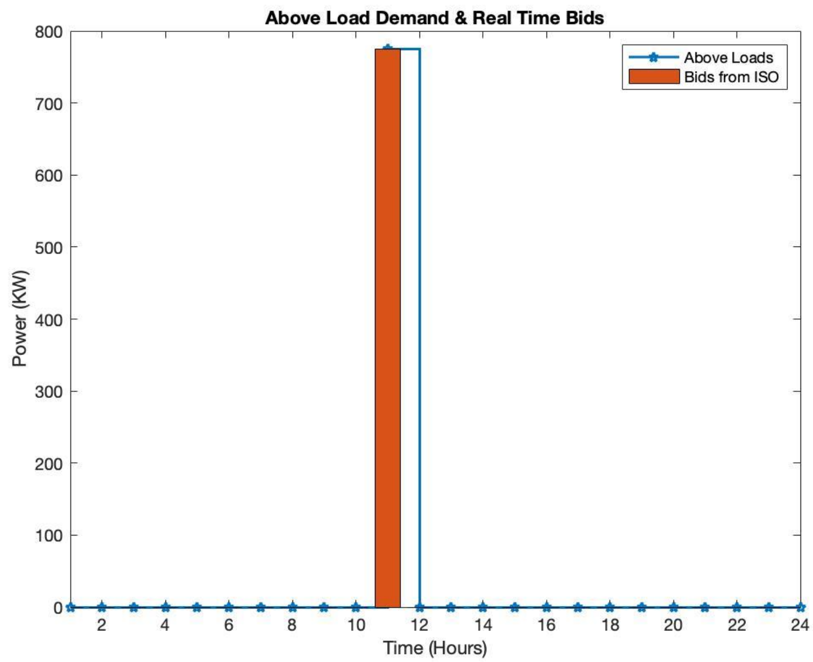

Figure 4.18 Above loads vs. real time bids

Due to the ability of the proposed virtual microgrid to work on an island mode, Figure 4.19 shows that all the customers in lower part of the system are supplied and not sheded from the available conventional and renewable sources with an amount of 3067 KW. The optimal restoration of the system shows that the summation of the bids purchased from ISO and the generated energy from the generators is equal to the total load of the system as in Figure 4.20.

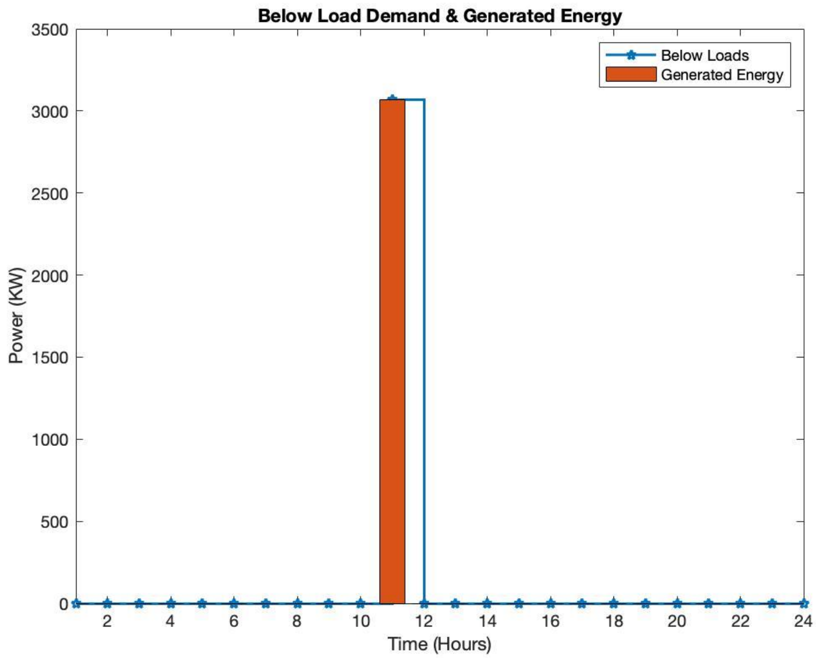

Figure 4.19 Below loads vs. generated energy

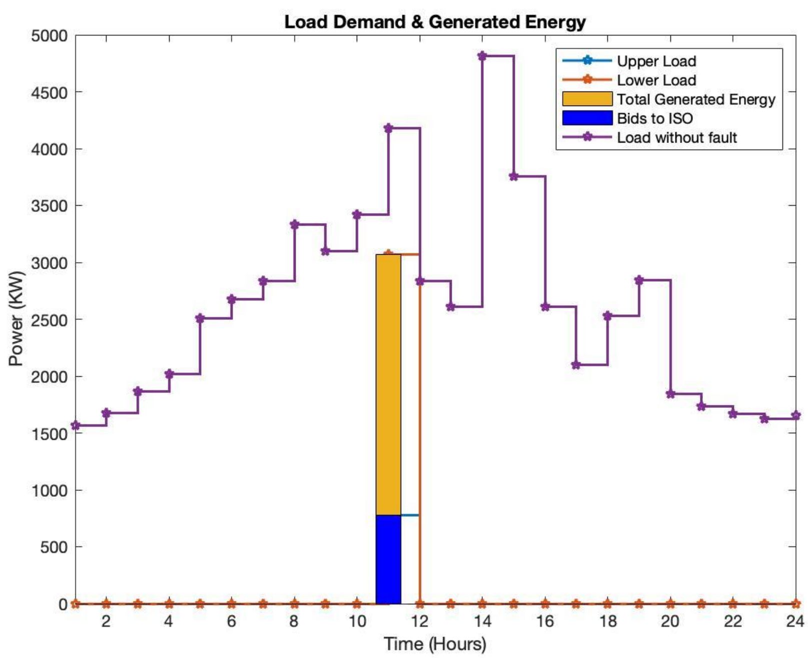

Figure 4.20 Optimal results of the system of case 3

The voltage of the system compared to the normal operation results is shown in Figure 4.21. Table 4.5 shows the results of the purchased energy compared to the loads in the above part of the system. In addition, it shows how much energy generated from the conventional generators and the renewable sources compared to the loads in the lower part of the system. It is clear that the proposed MILP technique of the virtual microgrid gives remarkable results assuming there is no losses in the system. The cost of the purchased energy from the ISO as well as the cost of the curtailed energy is shown in Table 4.6.

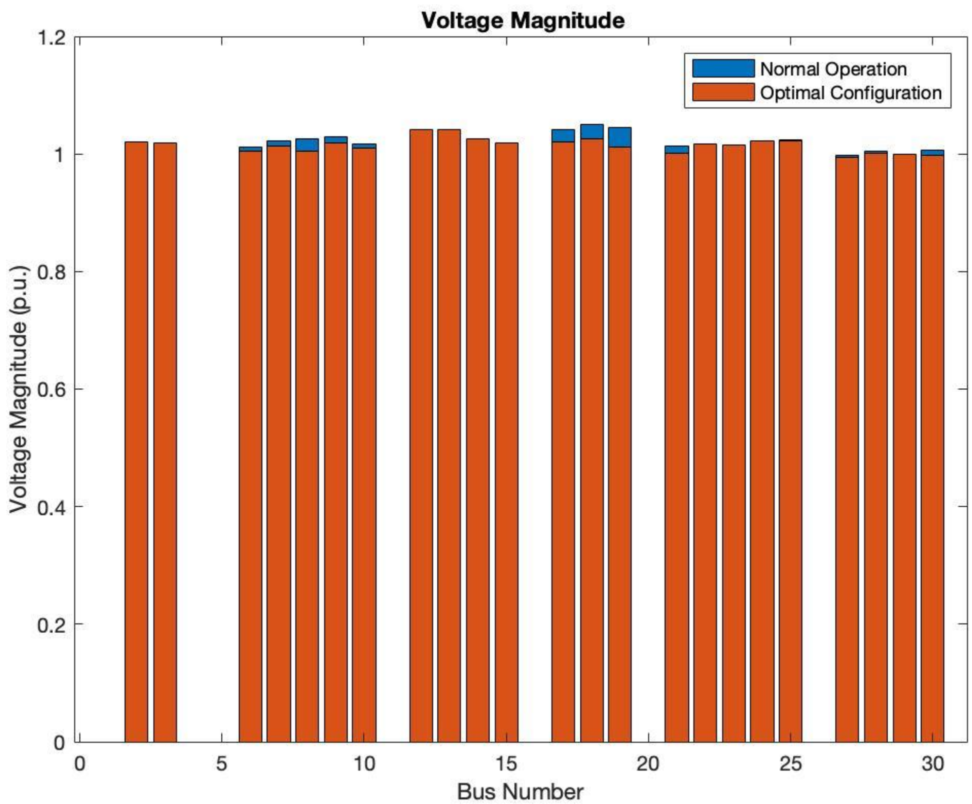

Figure 4.21 Voltage magnitude of case 3

Table 4.5 Optimization with EM vs. optimization without EM in case 3

	Optimization with EM	Optimization without EM
Total Loads (KW)	4181	4181
Loads After Fault (KW)	3842	3842
Lower Subsystem (KW)	3076	3076
Upper Subsystem (KW)	775.4	775.4
Bids (KW)	775.4 Buying	0
Generated (KW)	3076	3076

Table 4.6 Results of the optimized objective function in case 3

Number of Customers Restored	13
Curtailed Cost ($)	- 19.0362
Cost/PF ($)	- 61.0542
Total Cost/PF ($)	-80.0904

4.5 Case 4: Switching with Fault at L_{2-7}

Switching is considered when curtailment is not sufficient to restore and find the optimal configuration of the system. Few modifications on case 4 were applied where the loads are higher and the main grid limits is lower. These modifications made the curtailment insufficient when there is a fault in L_{2-7} since it impossible to restore all the loads by purchasing energy from ISO. As a result, switching is applied by the system in order to shed enough loads and restore the rest. Figure 4.22 shows the fault location and which branch is opened. The system shed the customers at bus 3 because they have the lowest priority weights among the upper loads. The amount of the lost loads at bus 3 is about 480 KW and the amount of purchased energy from ISO is around 580 KW as shown in Figure 4.23.

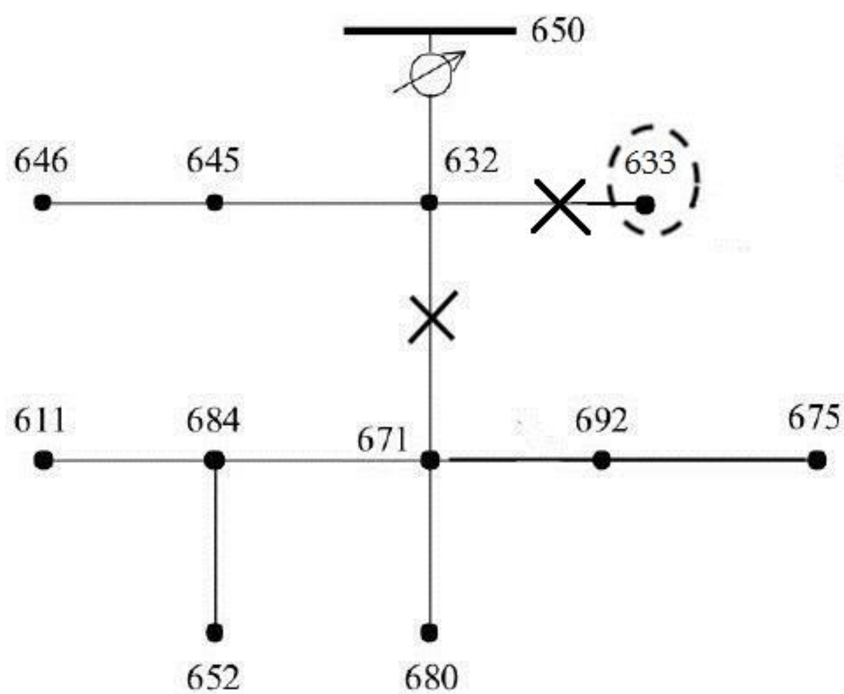

Figure 4.22 Case 4 with fault at line L_{2-7}

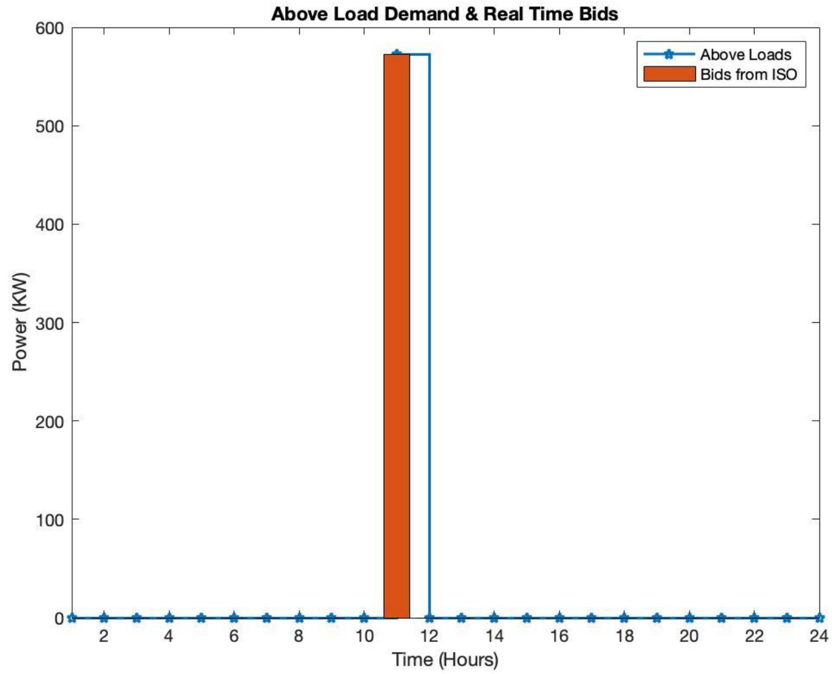

Figure 4.23 Above loads vs. real time bids

Because of the ability of system to operate in islanded mode, the lower loads are restored from the available conventional and renewable sources with an amount of 3303 KW as shown in Figure 4.24 and no switching was needed. Figure 4.25 shows that the summation of the bids purchased from ISO and the generated energy from the generators is equal to the total load of the system after fault. However, the system lost about 500 KW from the total load while in case 3 around 340 KW was curtailed.

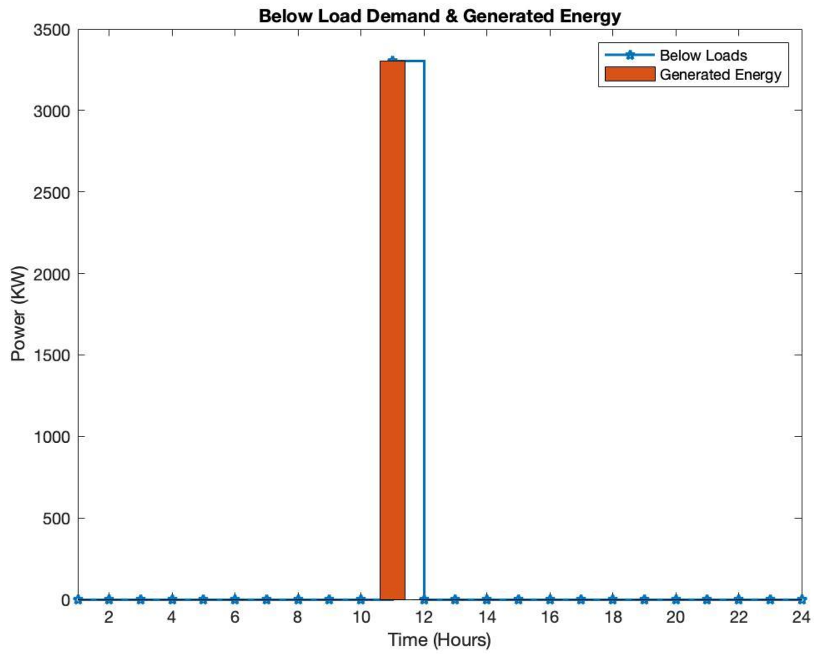

Figure 4.24 Below loads vs. generated energy

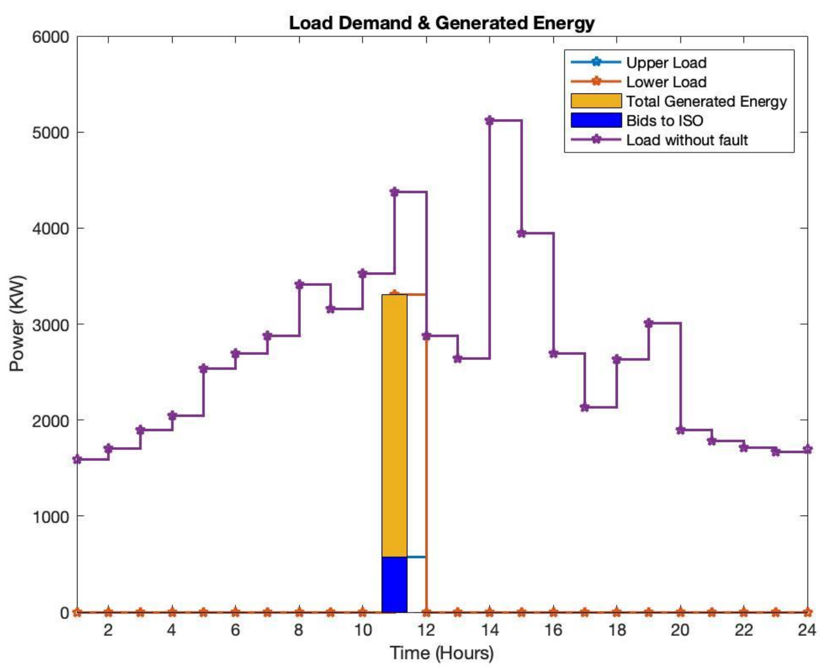

Figure 4.25 Optimal results of the system of case 4

Table 4.7 shows a comparison between the optimal results when applying curtailment and applying switching only. The results shows that both techniques find the optimal restoration service of the network. However, applying the curtailment technique is more efficient as it restored most of the system loads while the switching lost almost half of the upper loads. In addition, the generated energy from conventional and renewable sources are higher in switching than in curtailment.

Table 4.7 Optimization with switching vs. optimization with curtailment

	Optimization with switching	**Optimization with curtailment**
Total Loads (KW)	4362	4181
Loads After Fault (KW)	3876	3842
Lower Subsystem (KW)	3303	3076
Upper Subsystem (KW)	572.7	775.4
Bids (KW)	572.7 Buying	775.4 Buying
Generated (KW)	3303	3076

The cost of the purchased energy from the ISO as well as the cost of the curtailed energy as shown in Table 4.8. From the results, the switching technique restore 10 customers out of 13 while the curtailment technique restored 13 customers out of 13. In addition, the cost of buying energy from ISO using switching technique is about 45 dollars, which is less than 61 dollars in curtailment. That means applying curtailment is better in maximizing the number of restored customers while switching is better in minimizing the cost of participating in EM.

Table 4.8 Results of the optimized objective function in case 4

Number of Customers Restored	10
Curtailed Cost ($)	0
Cost/PF ($)	- 45.0805
Total Cost/PF ($)	-45.0805

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Summary

In this thesis, a restoration strategy of the smart grids was studied, analyzed and implemented in order to solve a problem phasing the current grids. Microgrid and VPP models were presented to increase the reliability and stability of the system. In addition, the concept of Virtual Microgrid was proposed by emerging the concepts of Microgrid and VPP. It provides the optimal configuration of the smart grid while participating in the EM to increase the profits or decrease the operation costs along with considering fault management. The FMSR problem was implemented as a multi-objective function and formulated and as a MILP technique because it is easier and faster for solving problems like FMSR than other optimization methods. The objectives of this thesis were to increase number of customers restored, increase the proposed system's profits, and decrease the curtailment cost. In addition, IEEE 13 bus test system was applied to present the proposed virtual microgrid system.

Three case studies were tested and simulated to verify the results of the proposed system where they were compared with the normal operation results of the system for verification. The first case study presented a fault in line $L_{4\text{-}5}$ where the customers in bus 5 cannot be restored. Since the proposed system was participating in EM, the results showed that the system was selling energy to the ISO because there was a day ahead bids calculated in the normal operation of the system for the customers were lost.

The second case study implemented as a fault in $L_{1\text{-}10}$ where complete conventional generator and the customers located in bus 1 were totally lost and cannot be restored. After implementing the proposed restoration technique to the system, the results showed that the system find another replacement of the energy lost from the conventional generator, it purchased the energy from the ISO and restored the rest of the customers in the network.

Finally, the third case study represented the core of the concept of the virtual microgrid where a fault was implemented in $L_{2\text{-}7}$ and two parts of the system were separated. The upper part contained only customers without any generators and the lower part contains conventional generators, renewable sources and controllable loads where it is not connected to the main grid. The results showed that the upper part was restored by purchasing energy from ISO, which state the concept of the VPP. While the lower part of the system was restored by generating energy from the available generators in the system while it works in an islanded mode which present the microgrid concept. All the three cases were simulated and implemented considering DS constraints and shows remarkable results compared to the normal operation results.

5.2 Conclusion

The following points can be concluded by observing the results of the case studies:

- The proposed virtual microgrid model successfully integrate the concepts of electrical microgrid and VPP, where it trades energy with the ISO at the same time of considering the FMSR problem.
- The results showed of the case studies showed that the proposed MILP approach of the virtual microgrid restoration was successful to restore most of the customers compared by the normal operation of the system.
- It was found that case 1and case 2 showed how the proposed system behave in the EM by analyzing the fault and all the available DGs sources considering the distribution network constraints and decide whether it will buy or sell energy with ISO.
- In the case study where the fault separates the system into two parts, all the customers in the upper part will be lost in the electrical microgrid. However, the virtual microgrid as able to restore all the customers in the upper part by purchasing energy from the ISO, as well as operating in an islanded mode for the lower part and use the conventional and renewable sources to restore the lower loads. In addition, applying the curtailment technique gives better results when it comes to maximize the number of customers restored compared with only applying switching.

5.3 Future Work

The work of this thesis can be extended as follows for future work:

- Optimize the priority model weights in order to provide a best and more accurate results regarding the restoration services.
- Implement the proposed FMSR problem of the virtual microgrid in different and larger system with a greater number of parameters.
- Implementing other optimization techniques on the virtual microgrid to make a general comparison between the results of these other methods with the results of the proposed approach of this thesis.

APPENDICES

A.1 Constraints Limits

A.1.1 Renewable Energy Limits

$$0 \leq \mathrm{PV}_{\mathrm{t}}^{\alpha} \leq 1000 \text{ KW} \quad (A.1)$$

$$0 \leq \mathrm{W}_{\mathrm{t}}^{\alpha} \leq 600 \text{ KW} \quad (A.2)$$

A.1.2 Conventional Generators Limits

$$0 \leq \mathrm{P}_{\mathrm{i,t}}^{\mathrm{Conv}} \leq 1000 \text{ KW} \quad (A.3)$$

$$0 \leq \mathrm{Q}_{\mathrm{i,t}}^{\mathrm{Conv}} \leq 1000 \text{ Kvar} \quad (A.4)$$

$$-200 \text{ KW} \leq \mathrm{P}_{\mathrm{i,t}}^{\mathrm{Conv}} \mathrm{P}_{\mathrm{i,t-1}}^{\mathrm{Conv}} \leq 200 \text{ KW} \quad (A.5)$$

A.1.3 Demand Response Limits

When the system is operating in normal condition, the limit for the accepted curtailed amount is assumed to be:

$$P_{i,t}^{LC} \leq 25\% \times L_{i,t} \quad (A.6)$$

When the system is operating in fault condition, the limit for the accepted curtailed amount is assumed to be:

$$P_{i,t}^{LC} \leq 40\% \times L_{i,t} \quad (A.7)$$

A.1.4 System Line Limits

$$0.95\text{ pu} \leq V_i^\alpha \leq 1.05\text{ pu} \tag{A.8}$$

$$-\pi \leq \theta_i^\alpha \leq \pi \tag{A.9}$$

$$\left|P_{ij}^\alpha\right| \leq 700\text{ KW} \tag{A.10}$$

$$\left|Q_{ij}^\alpha\right| \leq 700\text{ Kvar} \tag{A.11}$$

$$|SL_t^\alpha| \leq 1000\text{ KW} \tag{A.12}$$

A.2 Adopted Bus Numbering

Table A.1 The adopted bus numbering in the model

Bus Number as in Figure 3.1	Adopted Bus Number
611	1
632	2
633	3
645	4
646	5
652	6
671	7
675	8
680	9
684	10

A.3 Solar and Wind Generators Profiles

Table A.2 Wind Generators Forecast

Hour	Wind Generator Forecast (KW)
1	5.91
2	6.21
3	6.87
4	7.12
5	6.36
6	5.70
7	5.65
8	5.91
9	6.36
10	6.16
11	6.06
12	5.91
13	5.80
14	5.85
15	5.70
16	5.50
17	5.75
18	5.85
19	6.36
20	6.71
21	6.21
22	5.50
23	5.65
24	5.96

Table A.3 Wind Generator Forecast

Hour	Wind Generator Forecast (KW)
1	0.00
2	0.00
3	0.00
4	0.03
5	0.89
6	2.19
7	3.39
8	4.42
9	5.21
10	5.69
11	5.83
12	5.64
13	5.11
14	4.30
15	3.24
16	2.02
17	0.72
18	0.005
19	0.00
20	0.00
21	0.00
22	0.00
23	0.00
24	0.00

A.4 Load Priority Weights

Table A.4 Priority weights of customers

Bus	Number of Customers	Priority Weight		
1	1	0.0955		
2	0	0		
3	3	0.1753	0.6821	0.7012
4	1	0.8872		
5	1	0.8298		
6	1	0.9972		
7	3	0.1485	0.1144	0.4377
8	3	0.4143	0.1565	0.7474
9	0			
10	0			

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Experience and Activities

- Worked as Field Engineer in the Drilling Service department (DS) at Baker Hughes Saudi Arabia (2017)
- Worked with the Project Management Team (PMT) in the Pipeline & Communication Project Department (P&CPD) in Saudi Aramco (2015)
- Represented KFUPM as the Saudi delegation in China (2015)
- Volunteered in KFUPM voluntary day (2012,2013)
- Trained in Aramco summer training program for gifted students (2009)