ENHANCING THE RESILIENCE OF DISTRIBUTION POWER GRIDS WITH PHOTOVOLTAICS (PVs) AND ENERGY STORAGE

By

Alexander Lee McGirt

A thesis submitted to the Graduate Faculty of
University of North Carolina at Charlotte
in partial fulfillment of the
requirements for the degree of
Master of Science in
Engineering Management

Charlotte

2020

Approved by:

____
Dr. Linquan Bai

____
Dr. Churlzu Lim

____
Dr. Guanglin Xu

ABSTRACT

ALEXANDER LEE MCGIRT. Enhancing the resilience of distribution power grids with photovoltaics (PVs) and energy storage. (Under the direction of Dr. LINQUAN BAI)

Extreme events such as natural disasters can cause power grid failures, leading to catastrophic consequences and losses. With increasing integrations of photovoltaics (PVs) and energy storage in the distribution power grid, this work explores how to optimally utilize these distributed energy resources (DERs) to improve the operation efficiency and enhance power grid resilience. Improvement in resilience is obtained by incorporating both mobile and/or stationary battery storage systems along with solar power. The implementation of these two factors allow a system to become more responsive during disaster or unforeseen scenarios. Firstly, an optimization model was proposed for optimal scheduling and control of PVs and energy storage in distribution power grids to improve the operational efficiency. Secondly, this work exploited electric vehicles (EVs) as a type of mobile energy storage to enhance the power grid resilience when unforeseen events or disasters occur. Optimal allocation of these resources are implemented and utilized to improve system resilience.

DEDICATION

To my thesis advisor, Dr. Linquan Bai I express great appreciation in supporting me along my thesis journey. His provision of great advice and support allowed me to remain steadfast in my work. In addition to that I would also like to thank other faculty at the University of North Carolina at Charlotte for providing me with assistance to whatever hurdles I faced along the way. Additionally, I would like to thank my family and friends for supporting me throughout all of my academic journey.

BIOGRAPHY

Alexander McGirt grew up in Pembroke, North Carolina. With interest in engineering, the environment, and energy he went to the University of North Carolina at Pembroke to complete Pre-Engineering based coursework in 2013. Two years after that, he went to Charlotte, North Carolina to pursue a degree in Systems and Industrial Engineering. He graduated with a bachelor’s degree in Systems and Industrial Engineering from the University of North Carolina at Charlotte in 2018. In January 2019 he started his master’s studies at the University of North Carolina at Charlotte, with an interest in sustainability and energy. His graduate coursework has focused on logistics, supply chain, quality, energy, and modeling; research has brought him back to Engineering with applications in the areas of energy and efficiency.

ACKNOWLEDGMENTS

Initially I would like to thank my committee for allowing me to be a part of this project. I have been able to study something that I am interested in while being able to grow as a student and individual. Dr. Linquan Bai, you have a serious dedication to your work in addition to the students and others who collaborate with you. In my future endeavors I hope that I can operate with that much passion and dedication. Also, I would also like to recognize the other people whose incite, discussions, and contributions have benefitted this work. These individuals include: Dr. Guanglin Xu, Naveen Pani, Shaunak Prabhudesai, and other colleagues at UNC Charlotte. I would also like to thank my parents and other family and friends who supported me and stood by me during some of my most challenging moments. My presence and accomplishments to date would not exist if it weren't for you. Thanks for being with me and believing in me through it all.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

The current state of the U.S. power grid may be quite advanced compared to many others around the world, but it is still not perfect. Many steps towards improving the resilience and ruggedness of the U.S. energy system are needed to decrease its vulnerability in challenging scenarios like natural disasters [3]. Numerous papers propose solutions to help make the power distribution system more resilient through the utilization of different types of power generation sources [1]. Such can be done by optimally utilizing distributed energy resources (DERs) such as photovoltaics (PVs) and energy storage (ES) including both stationary and mobile units. A more efficient layout will allow for increased power generation by PV’s along with more in-need locations being supplied energy during disaster scenarios. With the proper positioning of ES units, the potential for load shedding can be reduced during natural disasters. Grid operating costs are reduced in relation to cases where stationary ES units and/or mobile ES (MES) units are not utilized [2]. Stationary ES units allow additional power capacity to be available for utilization in specific locations when made available. Implementing MES units would provide the same benefit, but with the gained improvement of flexibility so that varying locations in need of backup power can be reached. One potential area of MES units is electric vehicles (EVs). With the growing prevalence of these types of vehicles and their potential to both house and supply energy to the grid, their utilization is taken into consideration. This work focuses on utilizing PVs and ESs to improve the system operation and enhance the power grid resilience.

1.1. Photovoltaic Systems

Power grids commonly consist of a multitude of different types of generation and load sources. A high degree of complexity can be reached at times due to this. With that being the case, many efforts are put towards improving the efficiency and resilience of the power grid. To achieve this, various forms of renewable energy sources and backup power options are utilized when possible depending on the location and demand potential. One of the most popular renewable energy systems in use today are PV systems. The lower cost and increasing efficiency of PV systems make it more popular and affordable to adopt. Modern industrial PV systems can vary in output depending on solar cell material type and overall build quality. Solar PVs typically have efficiency levels around the 20% to 30% range with standard deviations caused by variables such as time of day, cloud cover and temperature among others [18]. However, PV power generation relies on the availability of sunlight so the occurrence of storms that limit light and nighttime periods with no light may limit the utilization of PV systems. In this case, energy storage is usually considered to be integrated into the power grid to coordinate the operation of PV systems.

1.2. Energy Storage Systems

As an emerging asset and technology, energy storage allows backup power supply to be located strategically throughout the PV systems and power grid in order to assist with any unmet power demand in the system. Available options like these prove to be very beneficial to have in critical and disaster-based situations. ES units can be either stationary or mobile, so versatility is an option [2]. One drawback to these systems is that they can be expensive. Since that is the case, a knowledgeable approach needs to be taken when determining the investment on ES units along with their locations of utilization.

There is increased interest in incorporating PV systems along with both stationary and MES systems into the power grid. These systems provide additional flexibility and grid services to support the power grid during times of contingencies. General PV system efficiencies have been increasing steadily over time, but variable power outputs throughout the day can act as a hindrance. Battery storage systems, or ES systems are becoming more efficient, but the limited battery capacity must be wisely utilized. As noted in [11], an ES system's ability to help in restoration efforts during situations such as black-start scenarios and other emergency situations is very advantageous. To help with extreme events of this nature, MES systems can be utilized in both pre and post stage processes to help alleviate issues. While stationary ES systems are somewhat limited in their utilization potential due to transportability, MES systems are more dynamic and flexible. They can supply power in almost any location as long as it is accessible. During normal operations both stationary and mobile ES systems can be used to help with fluctuating loads and also to relieve transmission congestion [12]. This makes MES systems ideal in disaster scenarios. Various optimization studies have been done on the use of ES systems regarding their siting, scheduling, as well as their sizing in both distribution and transmission systems [13]-[16]. As found in [17], a study was done that optimizes the utilization of mobile energy resources in preparing for a hurricane. Much research has been done in the ES area, but there is much more to be done.

1.3. Electric Vehicle Potential

Electric vehicles (EV) have increased in popularity over the years. The eco-friendly approach to transportation is in direct relation to the adoption of EVs regarding emissions and utilization of combustible fossil fuels. Due to these factors, EVs are projected to penetrate the automotive market considerably and have been rapidly in the past 10 years. It is forecasted that by the year 2030, as planned in the electric vehicle initiative campaign, there will be more than 43 million electric car sales made per year if a 30% market share of EVs is reached [3]. The demand for EV charging is set to increase exponentially soon. Total load on the system due to EV's alone will rise, as it is projected that more than 250 million EVs will be deployed globally by the year 2030 [3]. Thus, it is important to incorporate EVs into power grid operation. Various propositions have been made towards optimal charging management for EVs, so that will be considered as well to try to reduce the load on the power grid and costs to users. As a type of mobile energy storage, if appropriately utilized, EVs can contribute to the power grid operation and enhance power grid resilience.

1.4. Resilience

Improving the resiliency of power grid systems is no new topic in the energy industry. Many avenues and new approaches have been taken over the years by various entities. The power grid has become much more complex with various vulnerabilities to disaster scenarios. Introducing new approaches like ES unit utilization enhances the power grid resilience. With distributed energy resources (DERs) such as PV systems and ES units, the resilience of the power grid can be further enhanced by utilizing these flexible generation resources. However, incorporating these DERs make the system operation much more complex, thus, the challenges remain in how to optimally integrate and utilize PV and ES to enhance the power grid resilience.

Some previous research in the area of resilience within the power grid system involved the incorporation of various other components in parallel with ES unit allocation and utilization strategies to test unique scenarios. Recent research in the area of power system resilience has taken a variety of paths. This is vital due to the risks associated with catastrophic weather events and their negative impacts on both society as well as the economy [4]. As assessed in [5], the power grid resiliency can be analyzed through testing the vulnerability of transmission lines under varying load and weather conditions. With extreme weather conditions being unpredictable at times, the consequences of these events on the power grid can be significant [6]. Improved coordination, planning, preparation, and response efforts can help counteract such events and reduce their negative impact on the power grid and society. Improved response times to issues within power grids will help contain the issues and prevent them from propagating over to other systems and creating a cascading effect [7]. Actions like this will aid substantially in improving the overall efficiency and resiliency of an energy grid system. Since the range of catastrophic events can be very broad and complex in nature, it is hard for system operators to account for and develop countermeasures for all of them. Uncertainty in this regard is what makes power system resiliency such an important and applicable concept. Continuous aging of the power grid infrastructure is one of the elements that negatively impact the grid resilience [8]. The variability and uncertainty of renewable power generation will also impact the grid stability and resilience [9]. Resource adequacy during extreme events is another important concern in order to sustain resilient operations [10].

This thesis focuses on developing optimization models and algorithms to enable PVs and energy storage to improve system operational efficiency and enhance the power grid resilience. We also investigated the potential of EVs in enhancing power grid resilience under natural disasters or other unforeseen events. The proposed models and simulation results are presented in the following chapters.

CHAPTER 2: OPTIMAL OPERATION OF DISTRIBUTION POWER GREIDS WITH PVs AND ENERGY STORAGE

2.1. Nomenclature

Below is a list of the symbols and variables used in this thesis. A description is given for each in the nomenclature.

G	Set of distributed generators
X	Set of all the nodes in the network
X_s	Substation nodes
b	Node index
L	Set of all the distribution lines
$X(i)$	Set of nodes connected to node *i*
$P_{i,t,max}^{G}$	Maximum available power output of PV generator *i* at *t*
C_i^G	Inverter capacity of PV generator *i*
$P_{i,t}^{G}$	Active power output of PV generator *i* at *t*
$Q_{i,t}^{G}$	Reactive power output of PV generator *i* at *t*
$F_{i,\min}$	Power factor requirement of PV generator *i*
$w_{ij,t}$	Square of current in line i-j at time *t*
$u_{i,t}$	Square of voltage of node *i* at time *t*
M	Set of energy storage units
m	Index of the energy storage unit
e_{mt}	Energy state of charge of the m[th] energy storage [MWh]
$e_{m,t-1}$	Previous energy state of charge of the m[th] energy storage [MWh]

$p_{mbt}^{ch/dis}$	Charging/Discharging active power of storage m at bus b and time t
$ef^{ch/dis}$	Charging/Discharging efficiency
$e_{k,to}$	Initial energy state of charge of battery k [MWh]
$e_{k,t24}$	State of charge after 24 hours of battery k [MWh]
σ_{lt}^{l}	Switch state of line *l* at time t, 1 if connected, 0 otherwise (binary)
$P_{i,t}^{L}$	Active power load at node *i* at time *t*
$Q_{i,t}^{L}$	Reactive power load at node *i* at time *t*
P_{t}^{S}	Active power at the substation
Q_{t}^{S}	Reactive power at the substation
C_{sub}	Power capacity of the substation
$V_{i,t}$	Voltage of node *i* at time *t*
$V_{i,min}$	Minimum voltage level of node *i*
$V_{i,max}$	Maximum voltage level of node *i*
$I_{ij,t}$	Current on line i-j at *t*
r_{ij}	Resistance of distribution line *i-j* [Ω]
x_{ij}	Reactance of distribution line *i-j*
$P_{ij,t}^{f}$	Active power flow on line *i-j* at *t*
$Q_{ij,t}^{f}$	Reactive power flow on line *i-j* at *t*
$pr(i)$	The set of parent nodes of node *i*
$cd(i)$	The set of children nodes of node *i*
E_{m}^{max}	Energy rating of energy storage units [MWh]
P_{m}^{max}	Power rating of energy storage units [MW]
N^{ES}	Number of energy storage units
σ_{bt}^{d}	Load switch state, 1 if connected at bus b, 0 otherwise (binary)
$P_{ij,t}^{f}$	The active power flow in line i-j at time t

$Q^{f}_{ij,t}$ The reactive power flow in line i-j at time t

2.2. Mathematical Model

In this section, an optimization model was built for distribution power grid operation with PVs and energy storage. The operations and optimal dispatch of PVs and ES under normal scenarios are studied. Firstly, the PV system and energy storage models are presented. Then the distribution power grid operation model is formulated. Furthermore, the PV system and energy storage models are incorporated into the optimal operation model of the distribution power grid.

2.2.1. PV System Model

The inverters of PV systems can provide both active and reactive power. The active power output of a PV system is subject to the amount of solar irradiation. With this consideration, we can formulate the PV operation model as follows.

$$0 \leq P^{G}_{i,t} \leq P^{G}_{i,t,max} \tag{2a}$$

$$\left(P^{G}_{i,t}\right)^2 + \left(Q^{G}_{i,t}\right)^2 \leq \left(C^{G}_{i}\right)^2 \tag{2b}$$

$$-\frac{P^{G}_{i,t}\sqrt{1-\left(F_{i,min}\right)^2)}}{F_{i,min}} \leq Q^{G}_{i,t} \leq \frac{P^{G}_{i,t}\sqrt{1-\left(F_{i,min}\right)^2)}}{F_{i,min}} \tag{2c}$$

Thus, we have Eq. (2a) showing that the active power output of generators falls in between the maximum PV power output and a minimum of zero. The active power and reactive power from the inverter cannot exceed its capacity (apparent power). The sum of the square of active and reactive power output of a PV system is less than or equal to the PV inverter capacity squared as shown in Eq. (2b). The interconnection standards [20] of power utilities usually require the PV systems to operate within a range of power factor. Eq. (2c) shows that the reactive power output of PV inverter constraints is governed by the power factor requirement of a PV system. In this work, the PVs are operated in the range of 0.95 lagging to 0.95 leading power factor.

2.2.2. Energy Storage Model

A general energy storage model is presented as follows which describes the charging/discharging and energy transition in energy storage. It is applicable to both stationary and mobile energy storage.

$$e_{mt} = e_{m,t-1} + \sum_{b\in X}(p_{mbt}^{ch} * ef^{ch} - p_{mbt}^{dis}/ef^{dis}) \tag{2d}$$

$$0 \le e_{mt} \le E_m^{max} \tag{2e}$$

$$0 \le p_{mbt}^{ch} * ef^{ch} \le P_m^{max},\ \forall b \in X \tag{2f}$$

$$0 \le \frac{p_{mbt}^{dis}}{ef^{dis}} \le P_m^{max},\ \forall b \in X \tag{2g}$$

In the above model, Eq. (2d) considers the energy state of charge along with the charging and discharging power relative to their efficiencies. Energy storage constraints are set to a maximum limit of and a minimum of zero in Eq. (2e). Eq. (2f) and (2g) indicate that the charging and discharging power cannot exceed the maximum limit of the energy storage.

2.2.3. Optimization Model for Optimal Operation of Distribution Power Grids with PV and Energy Storage

An optimization model for optimal operation of distribution power grids with PV and energy storage is proposed. The second-order-cone (SOC) based branch flow model [1] is employed to model the power flow in the distribution power grid. The models of

PVs and energy storage are incorporated into the optimization model. Under normal conditions, the system operator aims at minimizing the total network loss.

$$min\ \sum_{t=1}^{24}\sum_{(i,j)\in L} r_{ij}w_{ij,t} \tag{2h}$$

s.t.

$$\sum_{k\in pr(i)}\left(P_{ki,t}^{f}-r_{ki}w_{ki,t}\right)-\sum_{j\in cr(i)}P_{ij,t}^{f}=P_{i,t}^{L}-\left(p_{mbt}^{dis}-\ p_{mbt}^{ch}\right)-P_{i,t}^{G},\quad \forall i\in X\backslash X_s,\ \forall t \tag{2i}$$

$$\sum_{k\in pr(i)}(Q_{ki,t}^{f}-x_{ki}w_{ki,t})-\sum_{j\in cr(i)}Q_{ij,t}^{f}=Q_{i,t}^{L}-Q_{i,t}^{G},\quad \forall i\in X\backslash X_s,\ \forall t \tag{2j}$$

$$u_{j,t}-\left(u_{i,t}-2(r_{ij}P_{ij,t}^{f}+x_{ij}Q_{ij,t}^{f})+(r_{ij}^{2}+x_{ij}^{2})w_{ij,t}\right)=0,\quad \forall j\in cr(i),\ \forall i\in X,\ \forall t \tag{2k}$$

$$V_{i,min}^{2}\le u_{i,t}\le V_{i,max}^{2},\quad \forall i\in X,\ \forall t \tag{2l}$$

$$0\le w_{ij,t}\le I_{ij,max}^{2}\forall(i,j)\in L,\ \forall t \tag{2m}$$

$$\|2P_{ij,t}^{f}\ 2Q_{ij,t}^{f}\ w_{ij,t}-u_{i,t}\|_2\le w_{ij,t}+u_{i,t},\quad \forall(i,j)\in L,\ \forall t \tag{2n}$$

The objective function is to minimize the total network loss shown in Eq. (2h). Eq. (2i) and (2j) depict the nodal balance equations for active power and reactive power, respectively. Eq. (2k) shows that the squared voltages are balanced across lines, relative to resistance, reactance and squared current and active and reactive power flow on the line. Squared voltage across branches is constrained by maximum and minimum voltage values as shown by Eq. (2l). Squared current across branches is constrained by the maximum current value and a minimum of 0 as shown in Eq. (2m). The summation of the squares of active and reactive power as well as the difference in current and voltage is constrained by the summation of current and voltage squared as shown in (2n), which is the second-order-cone representation in mathematics. The proposed second-order-cone programming (SOCP)-based optimization model can optimally dispatch the PVs and ES to minimize the total network loss and improve the system operation efficiency.

2.3. Case Study

In this section, simulations and case studies are conducted on different scenarios to demonstrate the effectiveness of the proposed model and show how the PVs and energy storage can be utilized to support power grid operations.

2.3.1. System Description

For any type of conclusions to be made a standardized test case needs to be utilized. In this work, the standard IEEE 33-node distribution system [19], as shown in Fig. 2.1, was used to test the proposed model.

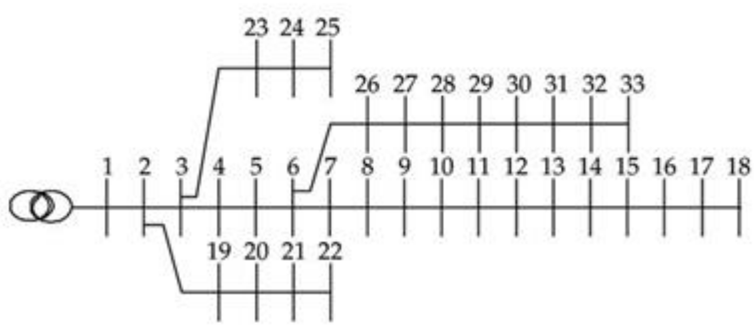

Figure 2.1: Diagram of IEEE 33-bus distribution system [19]

Table 2.1: Location and constraints of PV units

	Apparent Power	Max Power	Min Power
Bus #	S (kVA)	Pmax (kW)	Pmin (kVar)
18	350	310	0
22	520	470	0
25	330	305	0
33	500	450	0

Table 2.2: Location and constraints of energy storage units

	Power Capacity	
Bus #	Pmax (kWh)	Pmin (kWh)
5	300	100
12	400	100
21	300	100
30	400	100

In Table 2.1, the location of PV units across the power grid can be found. Each PV unit has its own constraints that must be adhered to. The first PV is located at bus 18 with an apparent power of 350 kVA and a maximum active power output of 310 kW. The second PV unit is located at bus 22 and has an apparent power of 520 kVA and a maximum active power output of 470 kW. A third PV system is located at bus 25 with an apparent power rating of 330 kVA and a maximum active power output of 305 kW. The fourth and final PV unit is located at bus 33 and it has an apparent power of 500 kVA with a maximum active power output of 450 kW. Each PV unit has a minimum power of 0 kVar. The voltage range for all nodes in the system is set to 0.95-1.05 per unit (p.u.).

Additionally, Table 2.2 shows the location and constraints of ES units across the power grid. The first ES unit is located at bus 5 and has a maximum power capacity of 300 kWh and a minimum power capacity of 100 kWh. The second ES unit is located at bus 12 with a maximum power capacity of 400 kWh and a minimum power capacity of 100 kWh. A third ES unit is located at bus 21 with a maximum power capacity of 300 kWh and a minimum power capacity of 100 kWh. The fourth and final ES unit is located at bus 30 with a maximum power capacity of 400 kWh and a minimum power capacity of 100 kWh. It is in this test case that the ES units are located at these bus locations. The proposed model is applicable to both stationary and mobile energy storage. For mobile energy storage, since they have the mobile capabilities they can be placed anywhere along the grid as needed.

2.3.2. Simulation Results

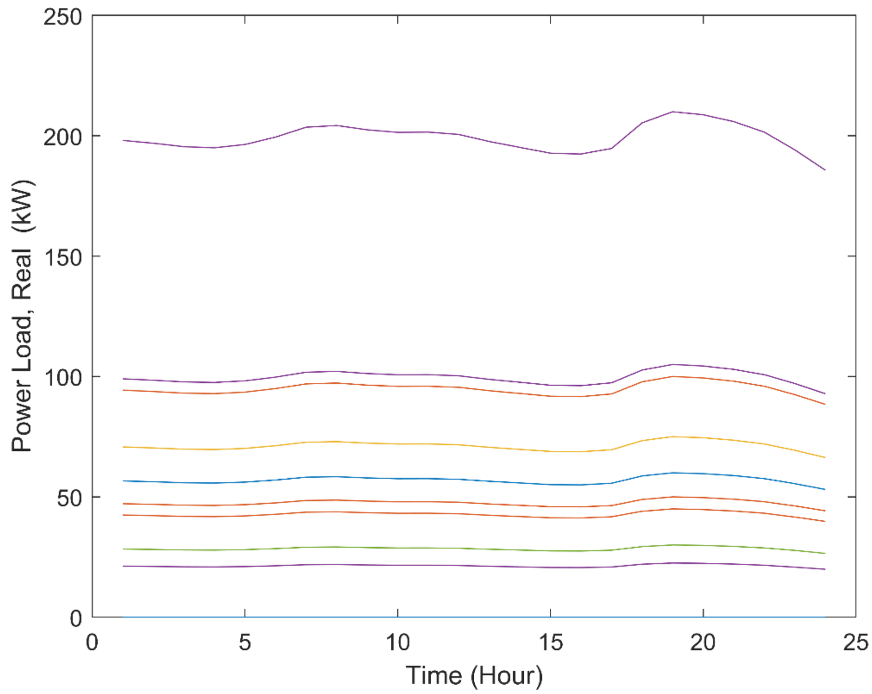

Figure 2.2: Active power load demand

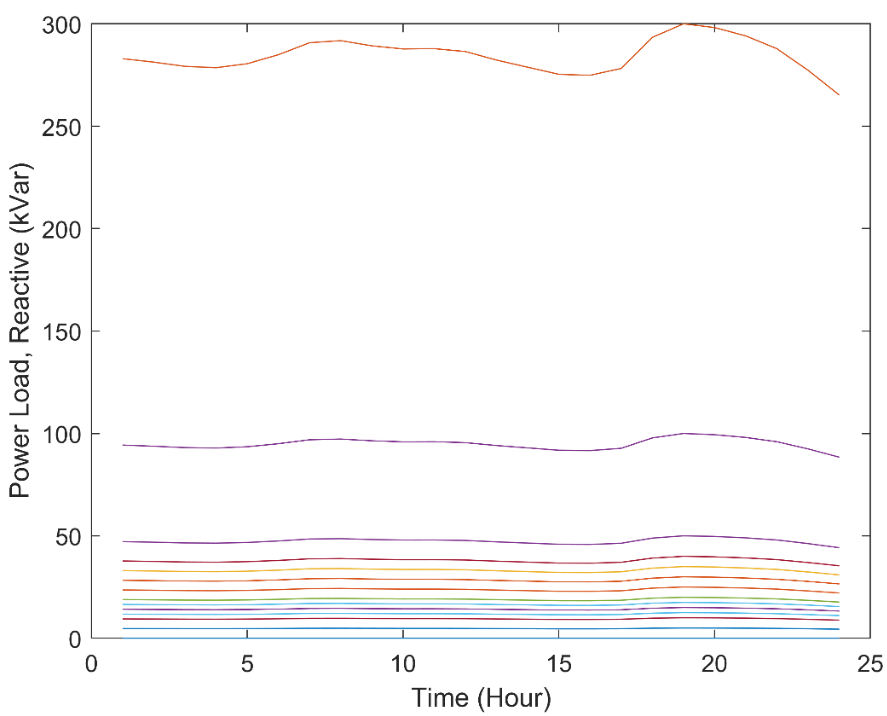

Figure 2.3: Reactive power load demand

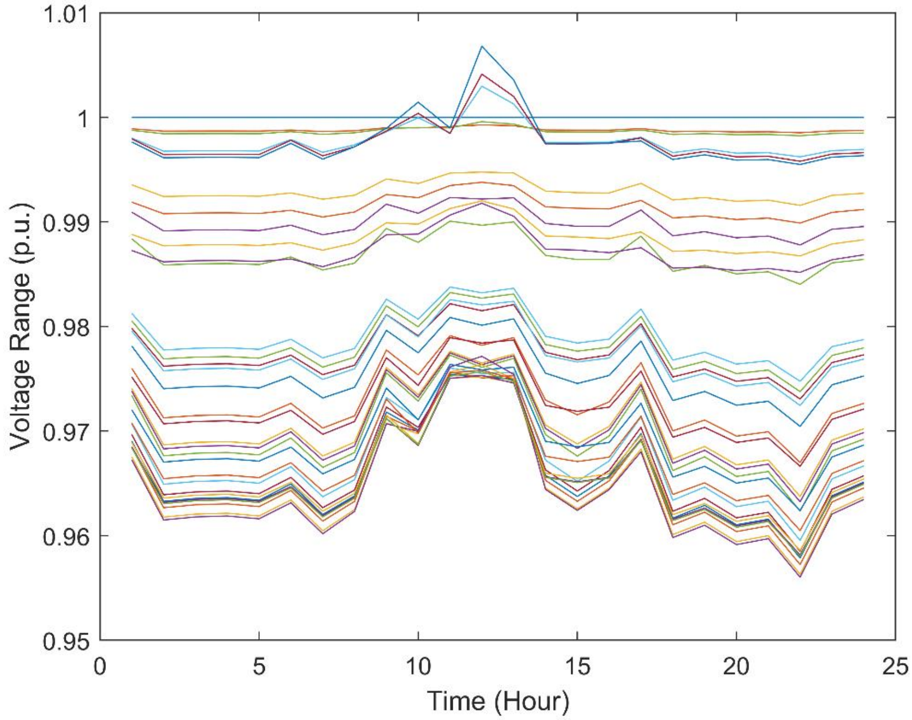

Figure 2.4: Voltage profile results across the power grid

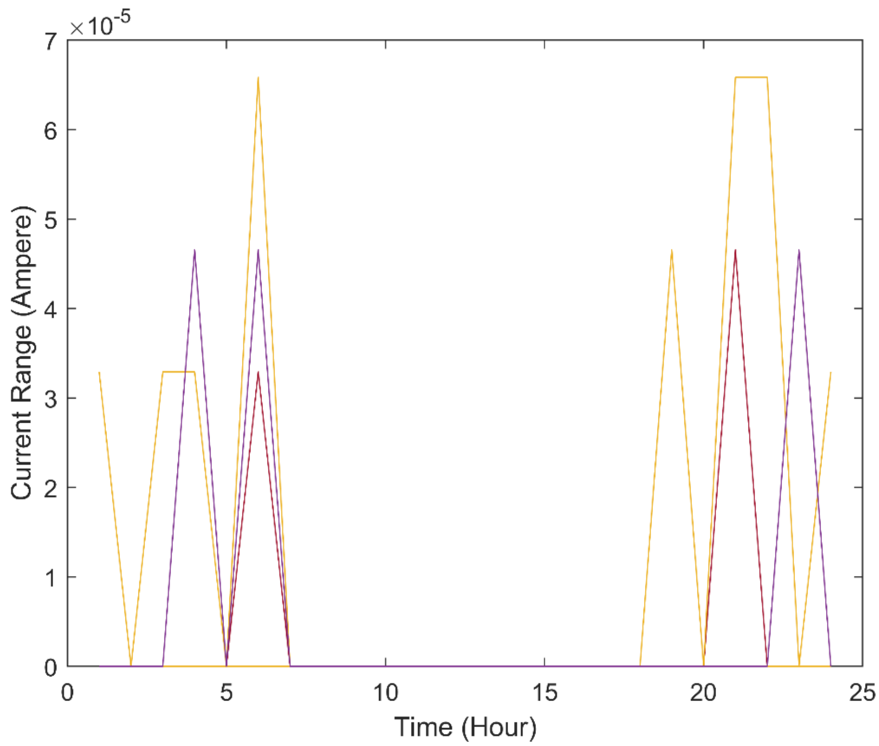

Figure 2.5: Current profile readings bus by bus

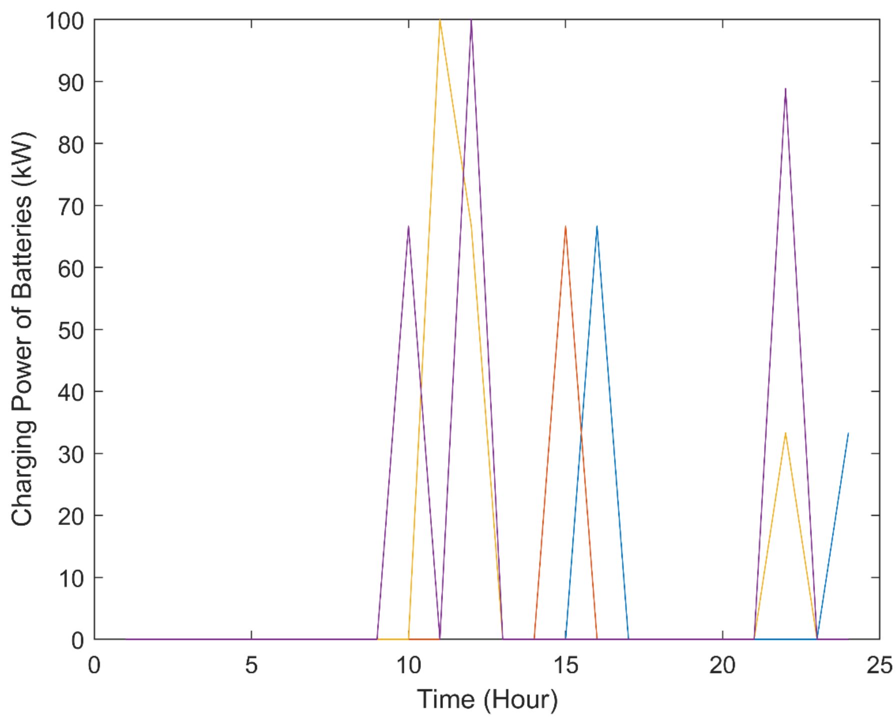

Figure 2.6: Battery charging rate

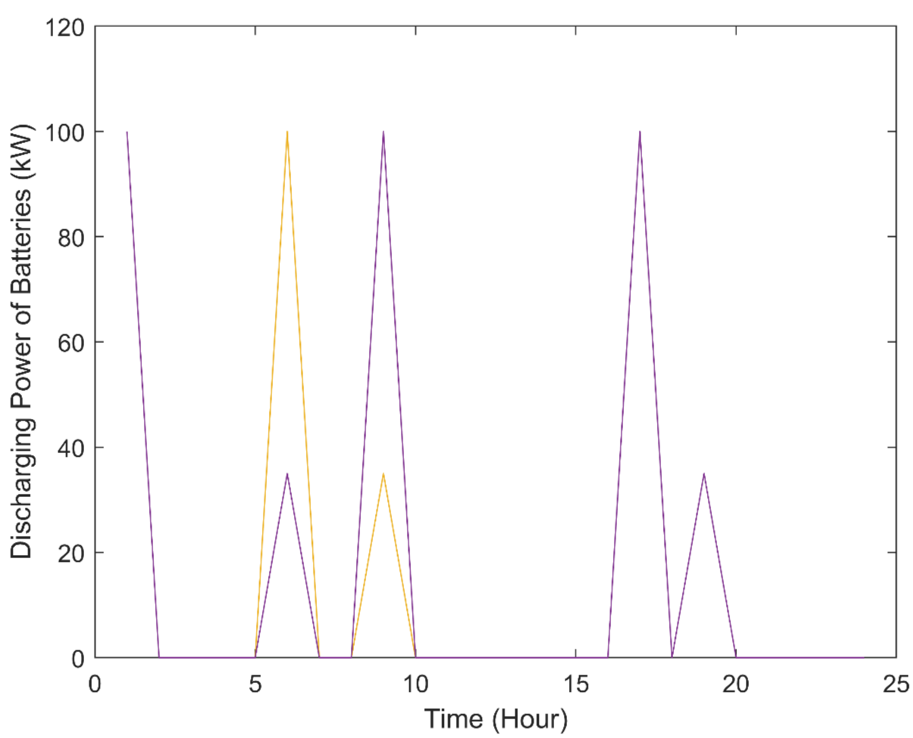

Figure 2.7: Battery discharging rate

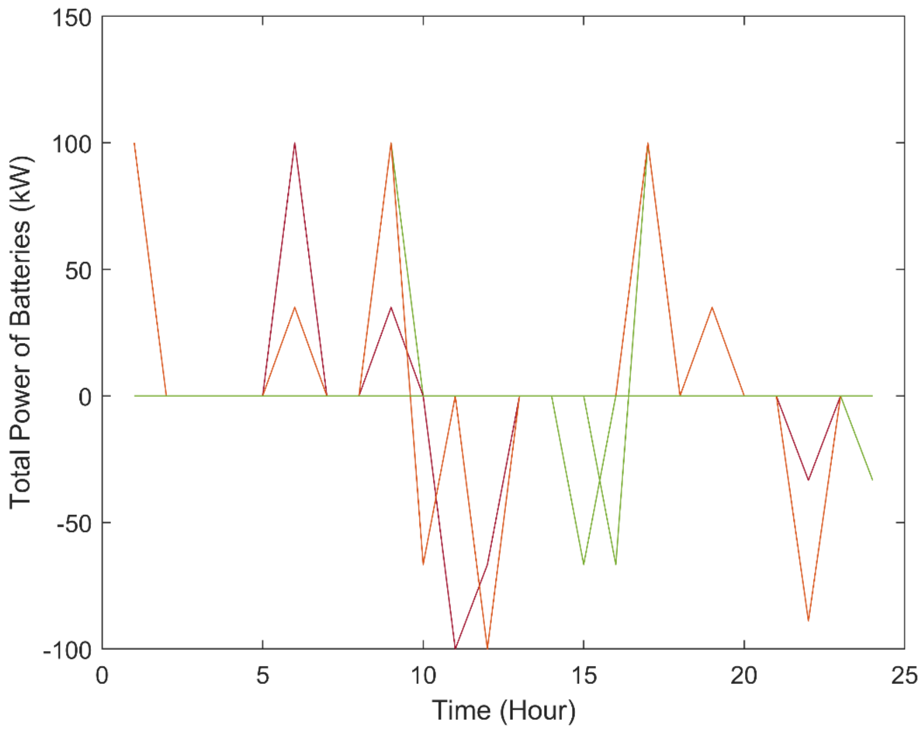

Figure 2.8: Battery state of charge

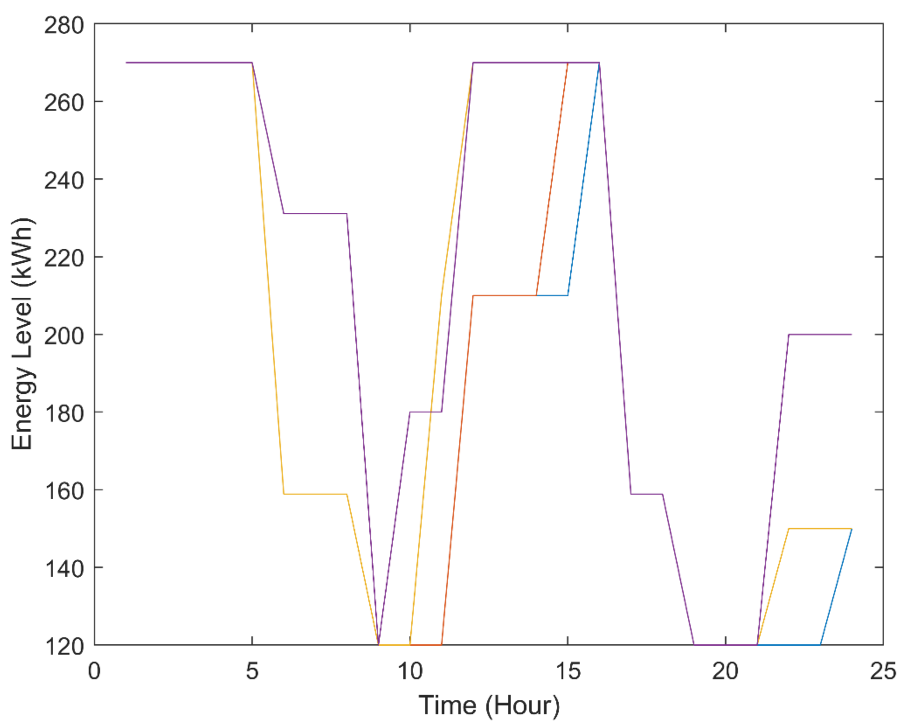

Figure 2.9: Battery capacity

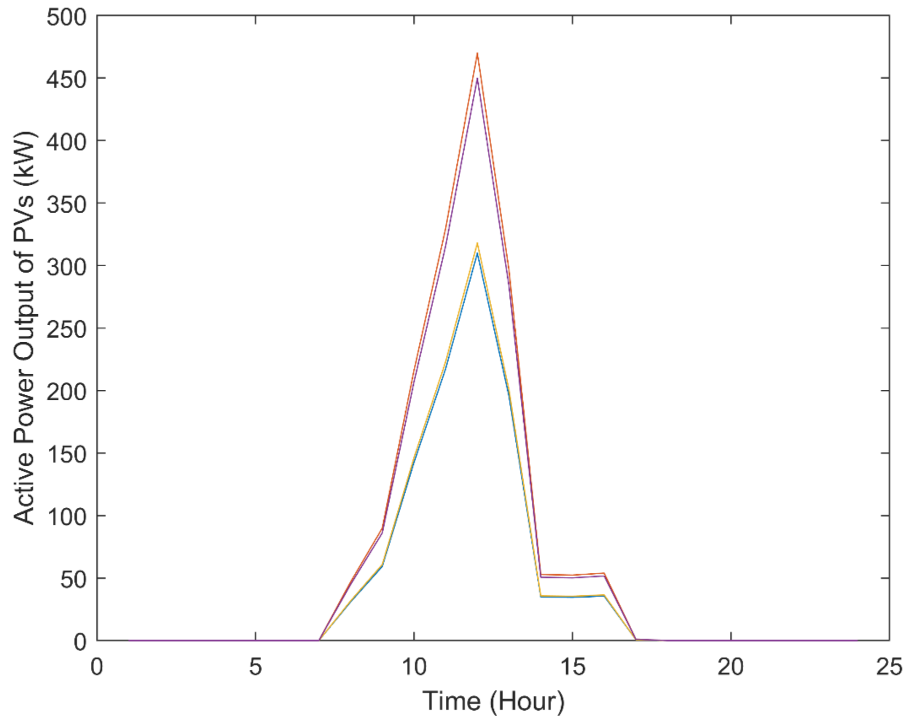

Figure 2.10: Active power profile of the 4 PV systems

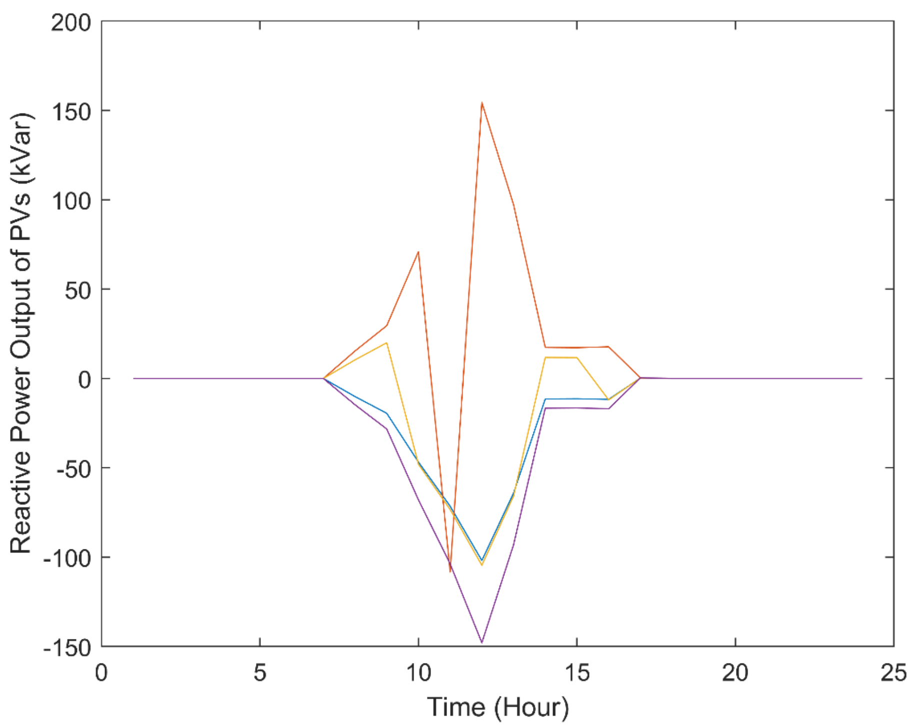

Figure 2.11: Reactive power profile of the 4 PV systems

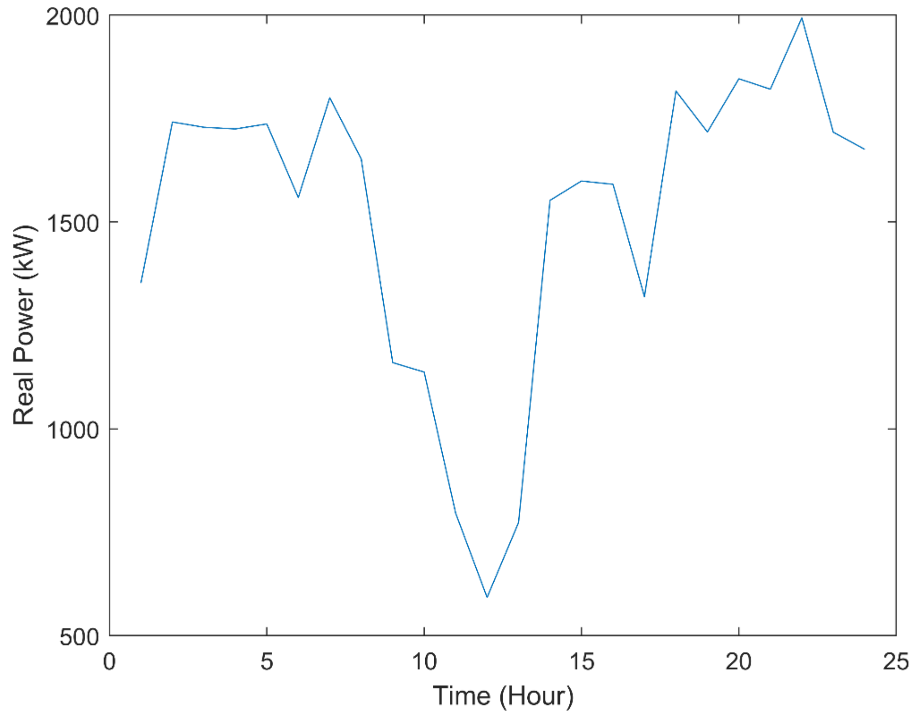

Figure 2.12: Active power from the substation

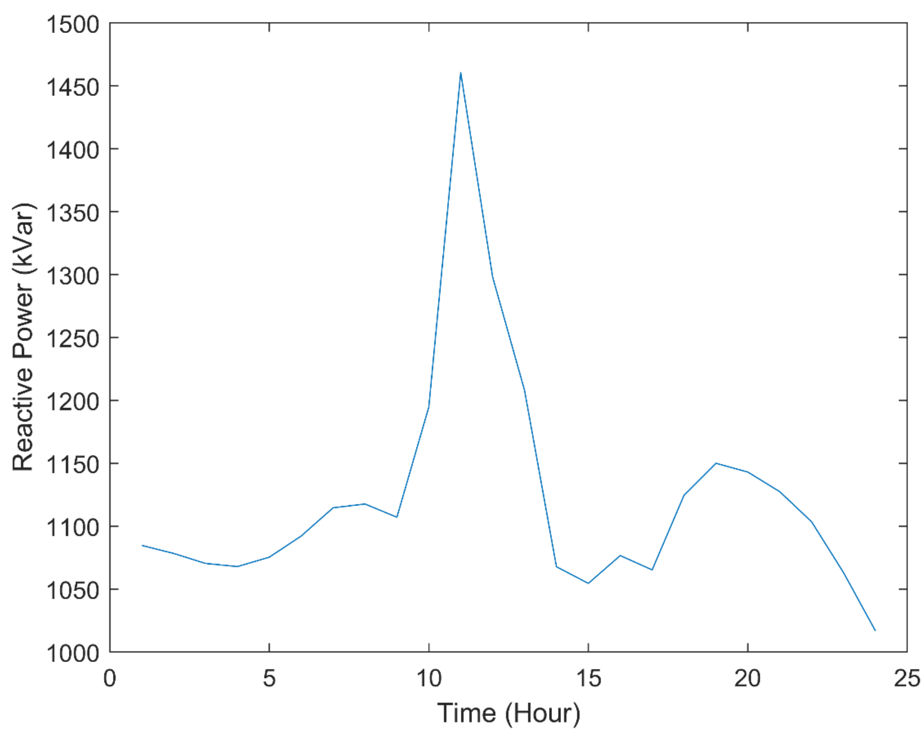

Figure 2.13: Reactive power from the substation

As shown in Figure 2.2, the active power load profile across all 33 nodes throughout the 24-hour time period is consistent. Load patterns at some nodes are identical. The same can be said for the reactive power as shown in Figure 2.3. Figure 2.4 illustrates the voltage profile results and it shows that the utilization of all 33 buses is maintained and how operations look in relation to the allowable limits. Note the impact incurred at nodes that have PVs and those with energy storage units. In Figure 2.5 current profile readings are shown node by node throughout a 24-hour time period. Results show that the operation at each node falls within the specified limits. Figure 2.6 shows the battery charging rate over a 24-hour time period. It shows the utilization of all energy storage units. Although that is the case, it appears that some are being used more than others. In Figure 2.7 the battery discharging rate over a 24-hour time period is shown. The utilization of all energy storage units is depicted. Figure 2.8 shows the battery state of charge levels over a 24-hour time period. It shows that normal hours of high-power demand lead to the utilization of the energy storage units. In Figure 2.9 the ES unit capacities, or energy levels, over a 24-hour period is shown. Energy levels tend to have slight utilization during early morning hours, then builds back up. Around the 8AM period high discharge is incurred by the batteries until around the 5PM time frame. At that point charging is experienced up until around the 10 PM time. This trend seems to be the case for all the energy storage units. Figure 2.10 shows the active, or real power profile of the 4 PVs, or solar panel systems in place on this power grid. Over a 24-hour period these units produce power during daylight operations as expected on a clear day. The hours of production start at around 8AM and end at around 5PM for all PV's. Some PV's have slightly different magnitudes of power, which could be to capacity as well as location-based factors such as weather and vegetation. In Figure 2.11 a reactive power profile of the 4 PVs in place have small amounts of power over the 24-hour period. The fluctuations in reactive power are noticeable during the hours of PV power generation, as expected. In Figure 2.12 real power output of the generator from substation, or the active power supplied by the main generator source at node 1 over a 24-hour time period is displayed. During hours of no sunlight the main generator source shows high rates of energy production. Contrary to that, during daytime periods (which has high grid demand) the output of this generation source decreases. This is due to the incorporation of PVs systems. To assist with meeting demand, ES units can assist throughout the entire day to help satisfy total demand. In Figure 2.13, the generation reactive power over a 24-hour time period is shown.

CHAPTER 3: RESILIENCE ORIENTED OPTIMAL OPERATION OF DISTRIBUTION POWER GRIDS WITH PVs AND EVs

In this chapter, we explore the values of electric vehicles (EVs) in enhancing the power grid resilience. In times when a natural disaster such as heavy storms or hurricanes, the distribution system operator (DSO) needs options on hand so that resilient actions can be taken to help system to be best prepared to mitigate the damages and losses [1]. The mobility of EVs can provide more flexibility and support to the power grid to sustain the natural disasters. The EVs can be routed to different locations in order to support the changing power grid operation during the disaster. In this work, we develop the optimal response plan and determine the locations of EVs that will be utilized for power injection to the power grid. We will explore and exploit the value of EVs as a type of mobile energy storage in enhancing the power grid resilience.

3.1. Mathematical Model

In this section, we present an optimization model for distribution power grid operation with PVs and EVs acting as mobile energy storage systems during emergency operating conditions. In the emergency conditions, one or multiple distribution lines may be tripped due to the disaster. The system operator will optimally allocate a fixed number of EVs to different locations in the distribution network and optimally control the PVs and EVs. If the contingency lines are changing dynamically due to the disaster, we can utilize the mobility of EVs and reallocate EVs to different locations. Different from the normal conditions in which the system operator aims at minimizing the total network loss, the DSO will minimize the total load shedding in the emergency or contingency scenarios.

3.1.1. EV Allocation Model

In a given distribution power grid, let N^{ES} be the total number of EVs and v_{mb} be the binary variable indicating the location of the EV. If EV m is located at node b, then v_{mb} = 1, otherwise v_{mb} = 0. With this consideration, we can formulate the EV operation model as follows.

$$e_{m,t} = e_{m,t-1} + \left(p_{mbt}^{ch} * ef^{ch} - p_{mbt}^{dis}/ef^{dis}\right) \tag{3a}$$

$$0 \leq e_{m,t} \leq E_m \tag{3b}$$

$$0 \leq p_{mb}^{ch} * ef^{ch} \leq P_m^{max} v_{mbt}, \forall b \in X,, \forall t \tag{3c}$$

$$0 \leq \frac{p_{mbts}^{dis}}{ef^{dis}} \leq P_m^{max} v_{mbt}, \forall b \in X,\ \forall t \tag{3d}$$

$$\sum_{b \in X} v_{mbt} \leq N^{ES} \tag{3e}$$

$$v_{mbt} \in \{0, 1\} \tag{3f}$$

Eq. (3c) and Eq. (3d) indicates that if $v_{mb} = 0$, the EV m is not located at node n and the charging and discharging power of the EV are limited to zero. In Eq. (3e), the number of dispatched EVs should not exceed the total number of EVs that are available.

3.1.2. Optimization Model for Optimal Operation of Distribution Power Grids with PVs and EVs in Contingency Scenarios

Under emergency operating conditions there are a few changes. One is that load shedding is incorporated and is penalized at the value of loss of load (C_{bt}^{VL}). Load shed is based on the real power demand (P_{bt}^{L}) along with the binary decision (σ_{bt}^{d}). The objective function, as shown in Eq. (3g), is utilized by the DSO to optimize the decision-making in utilizing EVs in the emergency scenario.

$$\min \sum_b \sum_t C_{bt}^{VL}(1 - \sigma_{bt}^{d}) P_{bt}^{L} \tag{3g}$$

The operational constraints in the contingency scenario are expressed as follows.

s.t.

$$\sum_{k\in pr(i)}(P^f_{ki,t} - r_{ki}w_{ki,t}) - \sum_{j\in cr(i)} P^f_{ij,t} = P^L_{it} * \sigma^d_{bt} - \left(p^{dis}_{mbt} - p^{ch}_{mbt}\right) - P^G_{it}, \quad \forall i \in X\backslash X_s, \tag{3h}$$

$$\sum_{k\in pr(i)}(Q^f_{ki,t} - x_{ki}w_{ki,t}) - \sum_{j\in cr(i)} Q^f_{ij,t} = Q^L_{it} * \sigma^d_{bt} - Q^G_{it}, \quad \forall i \in X\backslash X_s \tag{3i}$$

$$-M * \left(1-\sigma^l_{l,t}\right) \le u_{j,t} - \left(u_{i,t} - 2\left(r_{ij}P^f_{ij,t} + x_{ij}Q^f_{ij,t}\right) + \left(r^2_{ij} + x^2_{ij}\right)w_{ij,t}\right) \le M * \left(1-\sigma^l_{l,t}\right), \quad \forall j \in cr(i),\ \forall t, \forall i \in X \tag{3j}$$

$$V^2_{i,min} * \sigma^d_{bts} \le u_{i,t} \le V^2_{i,max} * \sigma^d_{bts}, \quad \forall i \in X \tag{3k}$$

$$0 \le w_{ij,t} \le I^2_{ij,max} * \sigma^l_{l,t}, \quad \forall (i,j) \in L \tag{3l}$$

$$\left\| 2P^f_{ij,t} \quad 2Q^f_{ij,t} \quad w_{ij,t} - u_{i,t} \right\|_2 \le w_{ij,t} + u_{i,t}, \quad \forall (i,j) \in L, \forall t \tag{3m}$$

$$0 \le P^G_{i,t} \le P^G_{i,max} \tag{3n}$$

$$\left(P^G_{i,t}\right)^2 + \left(Q^G_{i,t}\right)^2 \le \left(C^G_i\right)^2 \tag{3o}$$

$$-\frac{P^G_{i,t}\sqrt{1-\left(F_{i,min}\right)^2)}}{F_{i,min}} \le Q^G_{i,t} \le \frac{P^G_{i,t}\sqrt{1-\left(F_{i,min}\right)^2)}}{F_{i,min}} \tag{3p}$$

Building off the normal operation model, approaches to be taken during emergency operations need to be considered. Everything about the emergency operations model is the same as that in the normal operations except for the following changes. The load shedding variable (σ^d_{bt}) is incorporated into the right-hand side of equations (3j). $\sigma^l_{l,t}$ is the parameter representing the status of the distribution line *l* at time *t*. If $\sigma^l_{l,t} = 0$, then distribution line *l* is open, otherwise $\sigma^l_{l,t} = 1$. The Big-M method and $\sigma^l_{l,t}$ are utilized to model the power flow under contingency scenarios. Load loss in this scenario adds additional constraints with voltage levels across the distribution system (3k). Distribution line utilization constraint is incorporated into the right-hand side of the apparent power flow equation in

(3j) as well. When the distribution line is open, constraint (3j) is relaxed and (3l) will enforce the current and power flow on this line to be zero.

3.2. Case Study

3.2.1. System Description

In the emergency scenario, the fundamental layout of the power grid is kept the same regarding the positioning and capacities of the PV systems. In this case, however, lines 22, 29, 30 and 31 have been damaged and cut off line flow due to the disaster scenario. For reference purposes again as set up on the IEEE 33-bus Distribution System Layout, line 22 connects bus 3 to bus 23, line 29 connects bus 29 to bus 30, line 30 connects bus 30 to bus 31 and line 31 connects bus 31 to bus 32.

3.2.2. Simulation Results

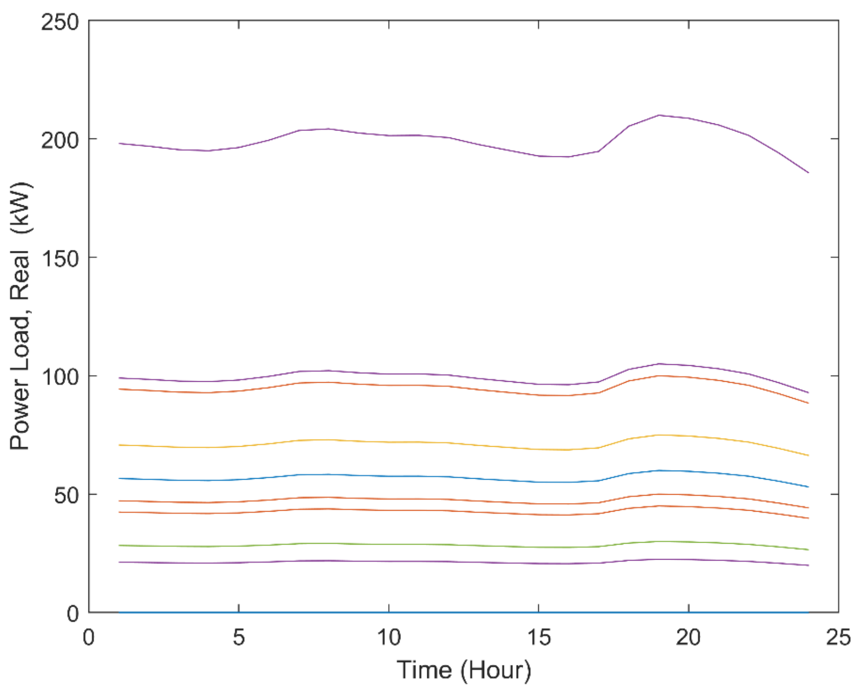

Figure 3.1: Active power load in the emergency scenario

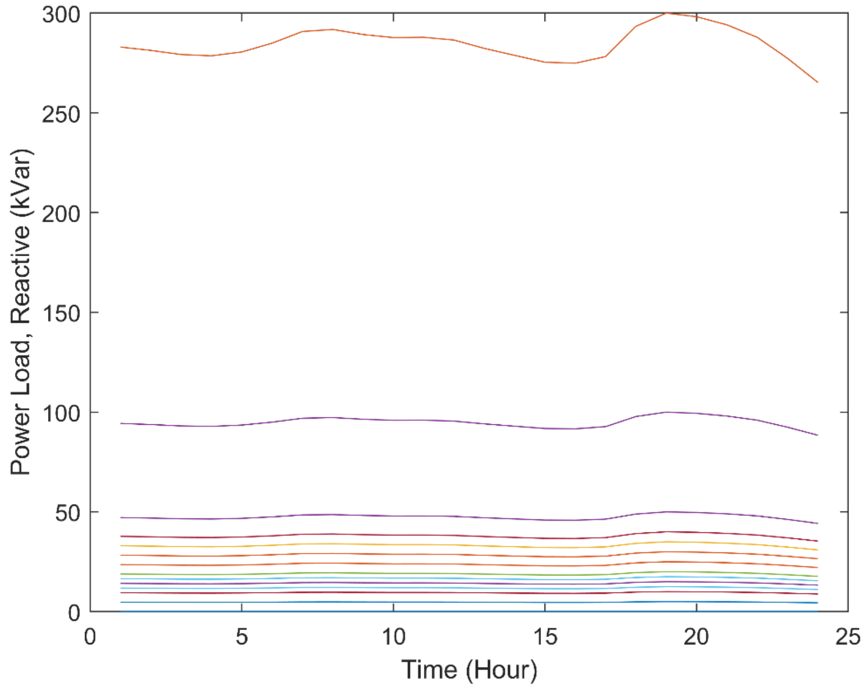

Figure 3.2: Reactive power load in the emergency scenario

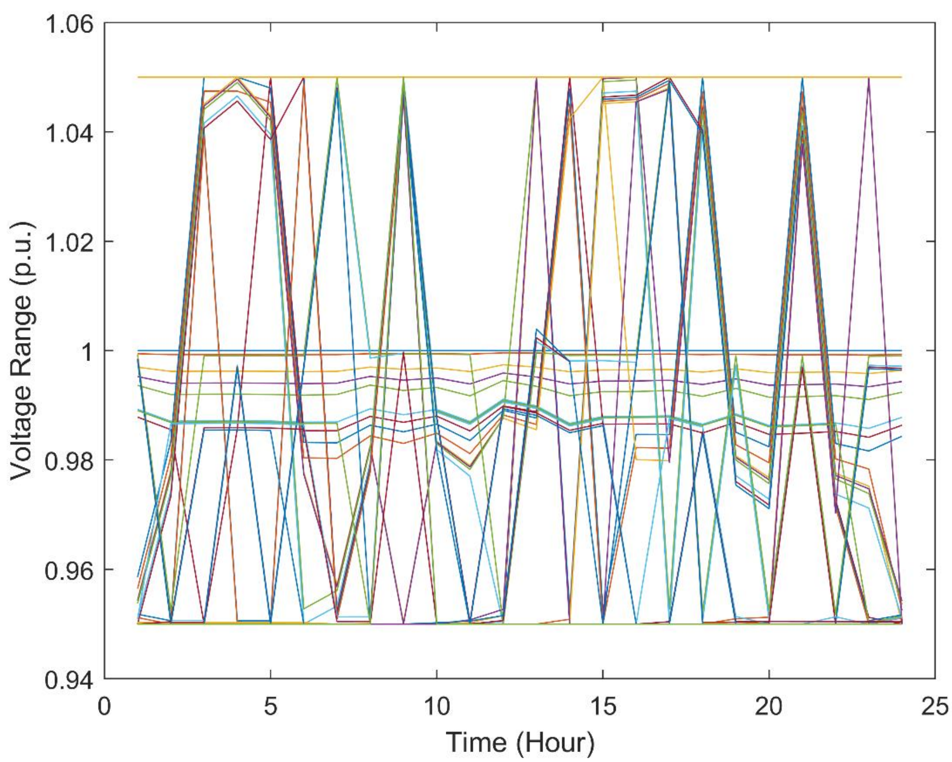

Figure 3.3: Voltage profile results across grid during emergency scenario

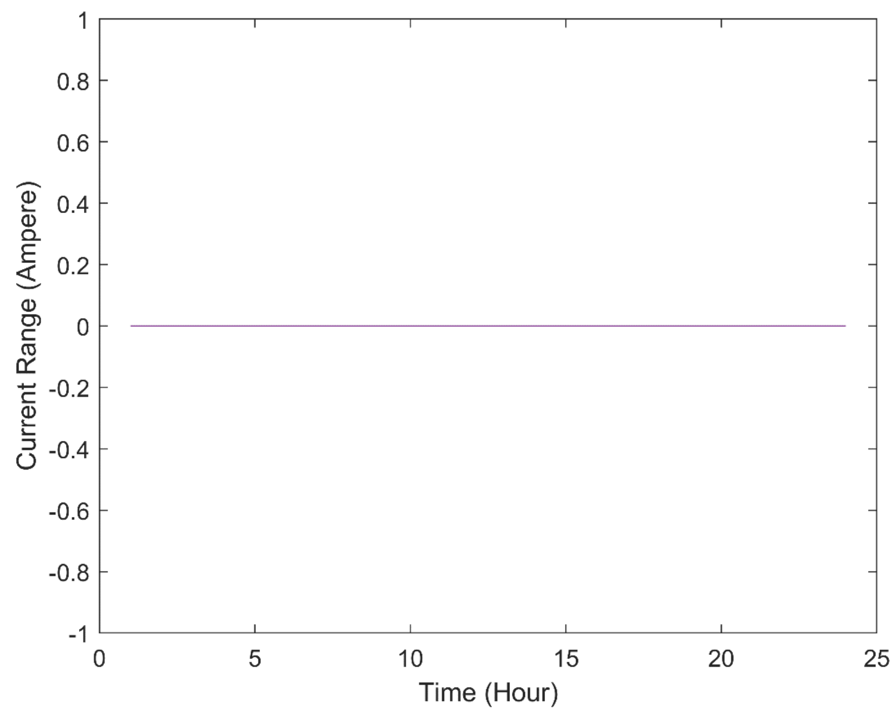

Figure 3.4: Current profile for disconnected lines in the emergency scenario

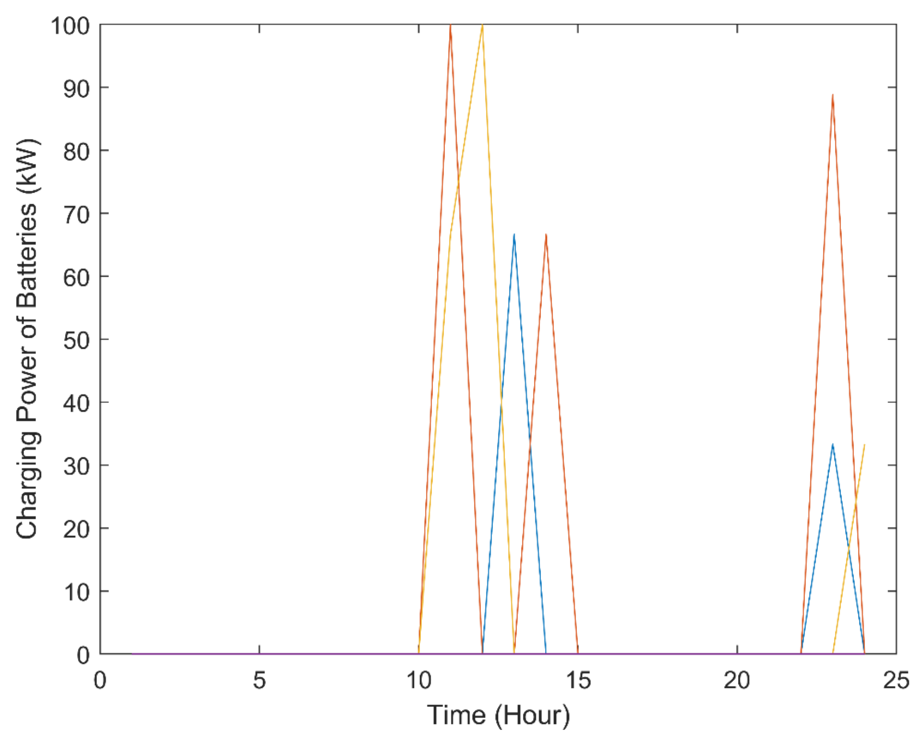

Figure 3.5: Battery charging rate in the emergency scenario

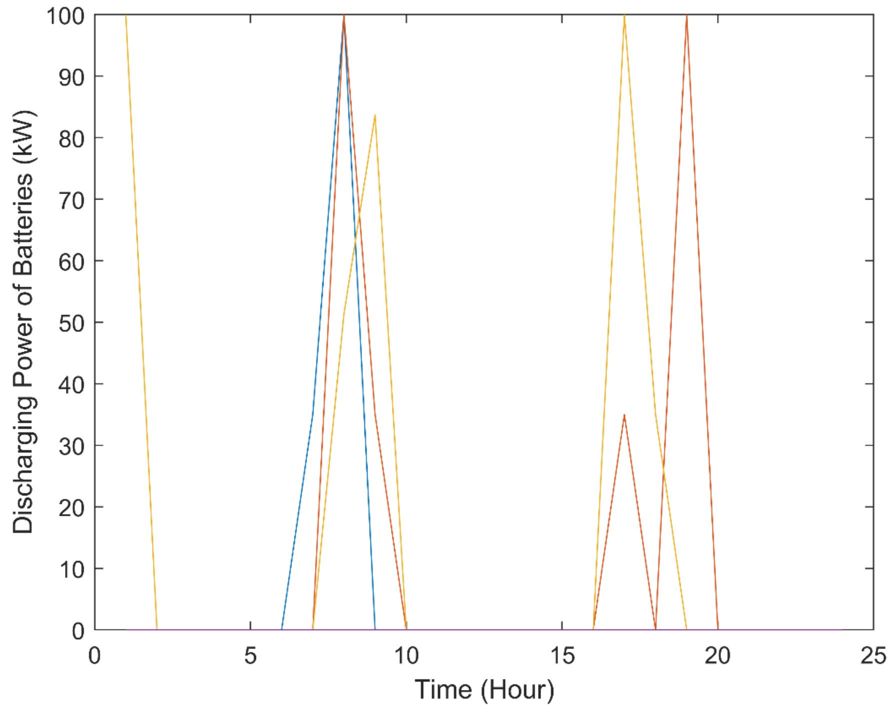

Figure 3.6: Battery discharging rate in the emergency scenario

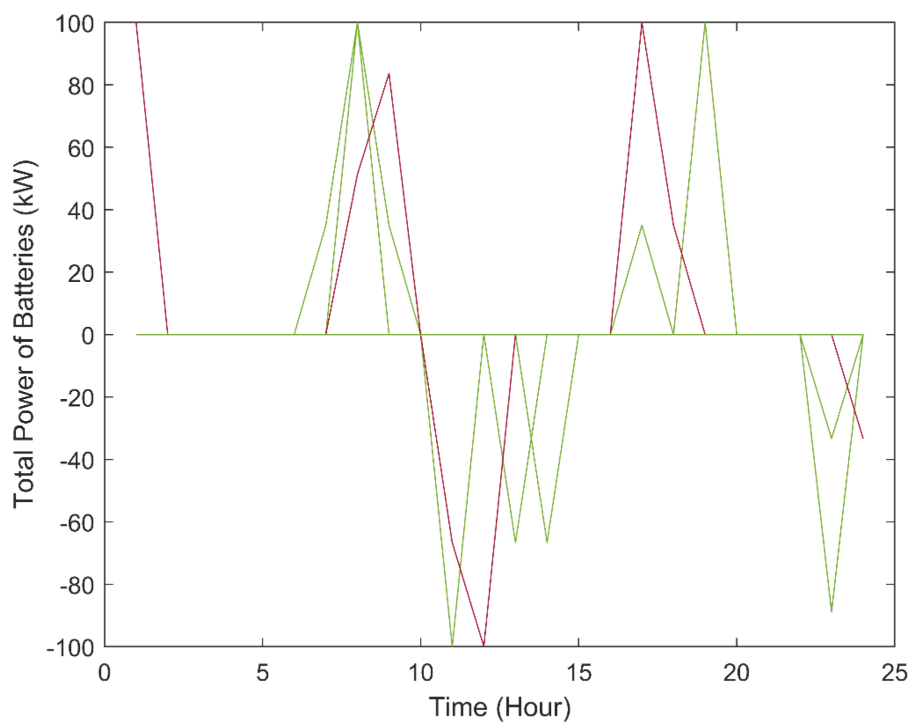

Figure 3.7: Battery state of charge in the emergency scenario

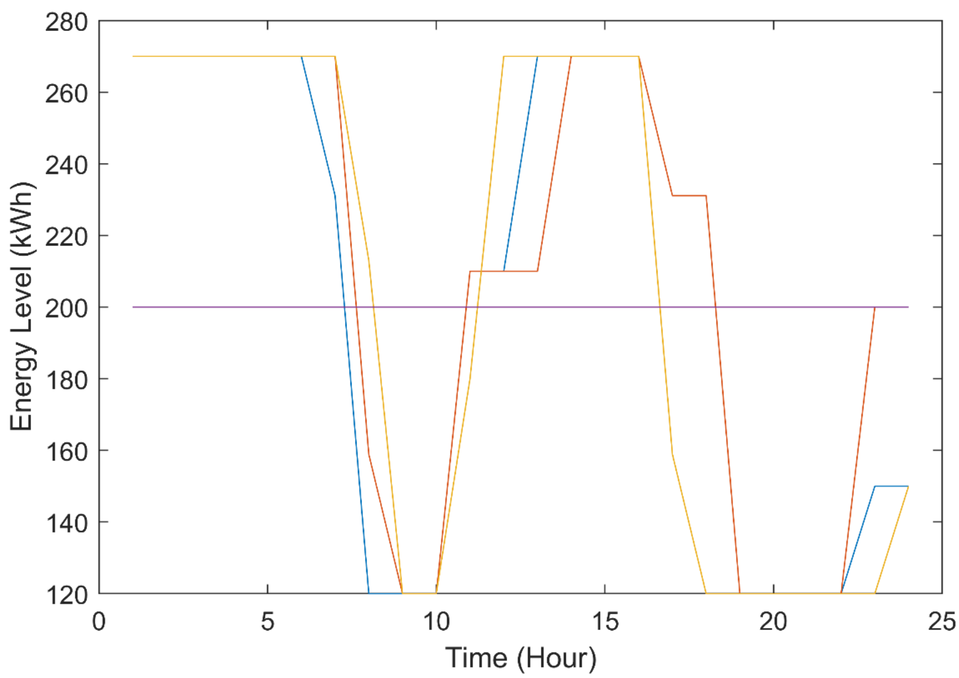

Figure 3.8: Battery capacity in the emergency scenario

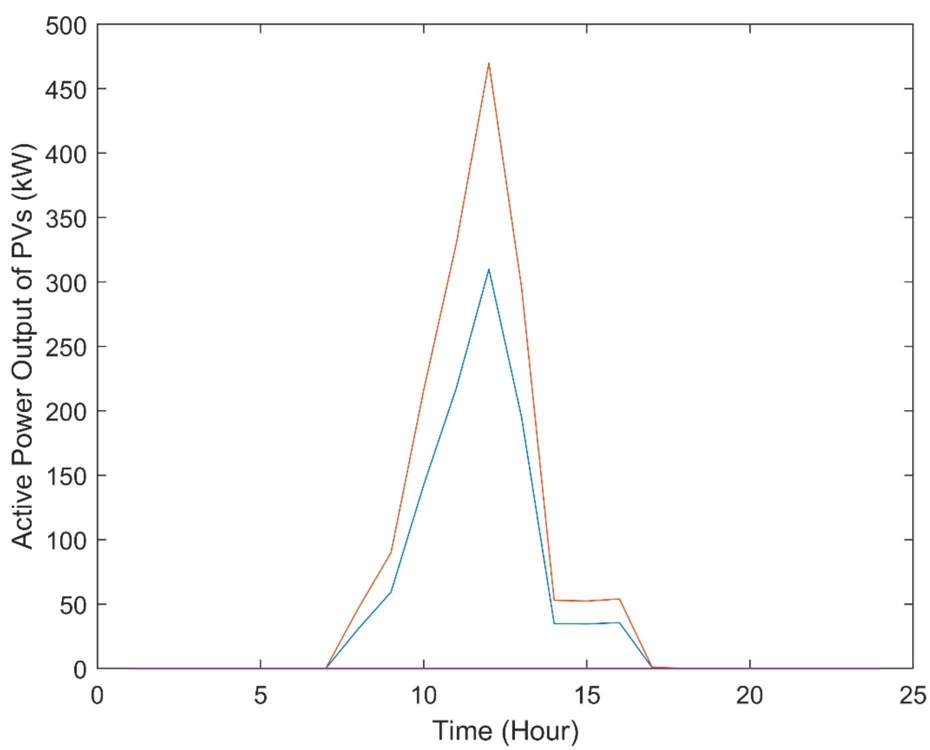

Figure 3.9: Real power profile of the 4 PV systems in the emergency scenario

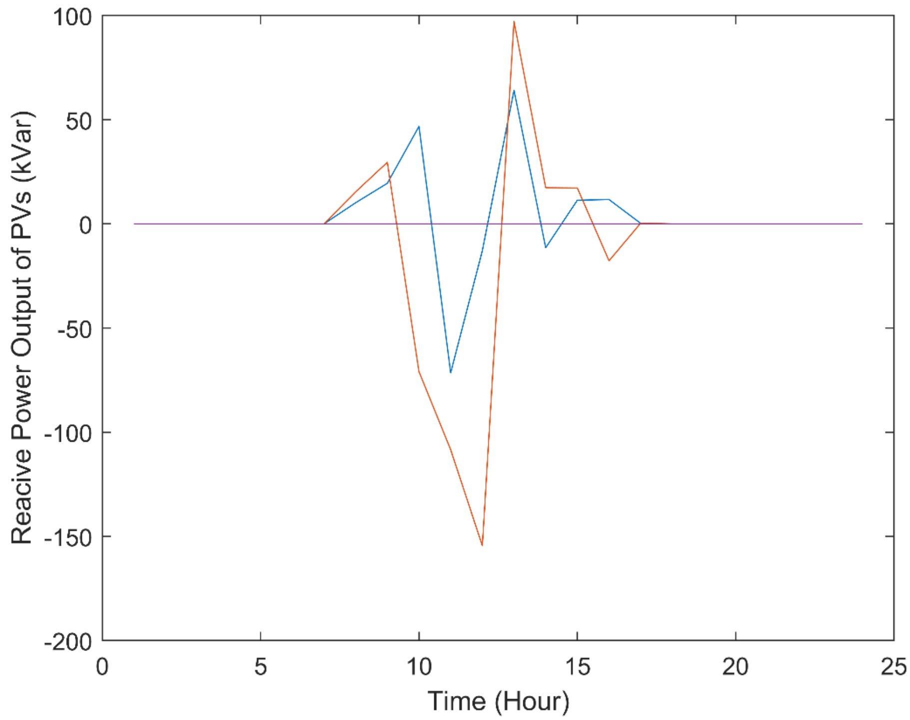

Figure 3.10: Reactive power profile of the 4 PV systems in the emergency scenario

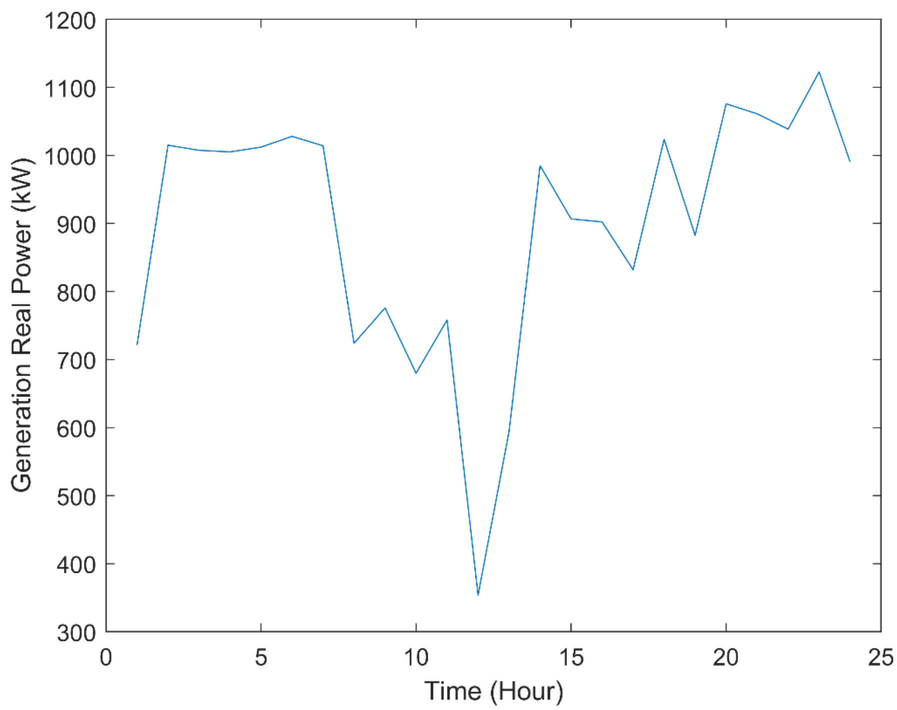

Figure 3.11: Active power from the substation in the emergency scenario

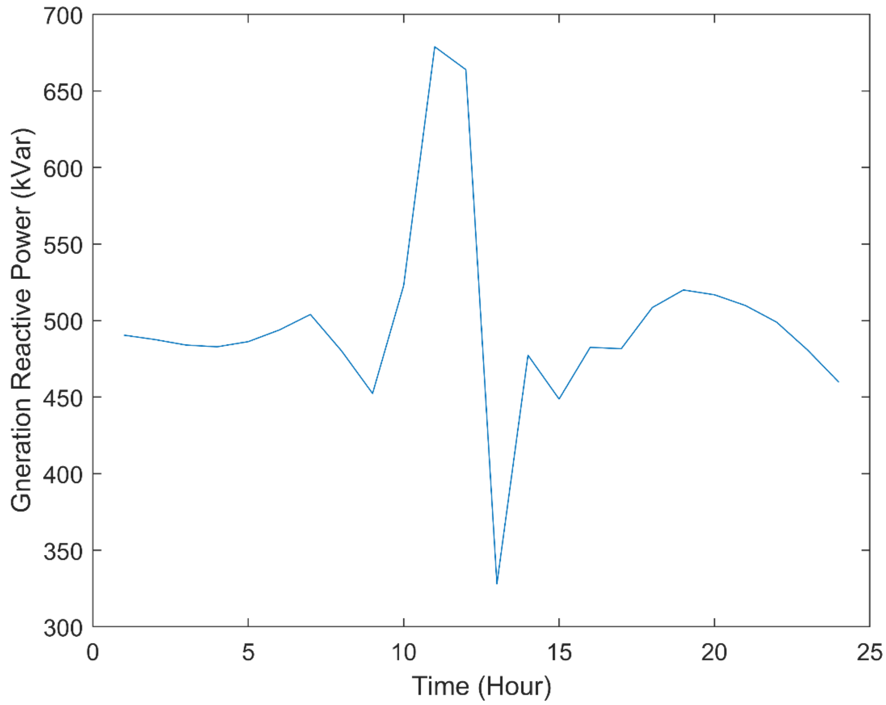

Figure 3.12: Reactive power from the substation in the emergency scenario

As shown in Figure 3.1, the active power load on all 33 nodes throughout the 24-hour time period is consistent and is the same as during normal operations. The same can be said for the reactive power in Figure 3.2. Figure 3.3 illustrates the voltage profile results and it shows a higher degree of variation compared to normal operations, but voltage levels fall within the acceptable limits. Note the impact incurred at nodes that have PV's and those with mobile energy storage units. In Figure 3.4, current profile readings are shown node by node throughout a 24-hour time period and the results show a reading of 0, although the current readings are known to be minimal. Figure 3.5 illustrates the battery charging rate and it shows the utilization of 3 mobile energy storage units. It still appears that some are being used more than others during hours of high demand. In Figure 3.6 shows a higher utilization of battery units over the 24-hour time period. The utilization of 3 mobile ES units is depicted in the discharging case as well. In Figure 3.7 the battery state of charge levels has a similar distribution and utilization as during normal operations, but there is a higher degree of variation during emergency operations. In Figure 3.8 the ES unit capacities have a similar pattern to during normal operations, but just with one less ES unit being utilized. Figure 3.9 shows that the active power profile of the PV in place has a similar amount of output, just with 2 less PV units being utilized. The reactive power profile in Figure 3.10 of the 2 PVs being utilized have slightly lower magnitudes of reactive power compared to normal operations. Active power supplied by the substation located at node 1 is less compared to during normal operations as shown in Figure 3.11. This change could be due to a variety of factors like down, or inactive lines and faulty signals. In Figure 3.12 the reactive power from the substation is significantly less, as expected due to the lower levels of active power being supplied.

To further study the value of EVs in enhancing power grid resilience, it is assumed that there are totally 20 EVs available to dispatch and the capacity of each EV is 40 kWh. The maximum charging and discharging power of an EV is set to 40 kW. The 20 EVs need to be dispatched and rerouted to different locations to pick up as much load as possible in the scenario that any of the distribution lines are tripped and the power supply services become interrupted. A larger voltage range is allowed with limits from 0.9 to 1.1 p.u..

We conducted simulation studies in the following scenarios and run the proposed optimization model in 3.1.

Scenario 1-a: Line 3-23 is in contingency and EVs are not utilized to support the grid;

Scenario 1-b: Line 3-23 is in contingency and EVs are utilized to support the grid;

Scenario 2-a: Line 3-23 and Line 2-19 are in contingency and EVs are not utilized to support the grid;

Scenario 2-b: Line 3-23 and Line 2-19 are in contingency and EVs are not utilized to support the grid;

In Scenario 1-a, when Line 3-23 is tripped, the feeder will be islanded leading to load shedding of 930 kW. If EVs are incorporated and dispatched to support the power grid in Scenario 1-b, all the 20 EVs are connected to Node 25 and the load shedding is decreased to 420kW. The load on Node 23, 24 and 25 are 90 kW, 420 kW, and 420 kW, respectively. The 20 EVs can pick up loads at Node 23 and 25 but do not have enough power to pick up the 420 kW load at Node 24. The voltage profile for Scenario 1-b is shown in Figure 3.13. Figure 3.13 demonstrates that the nodal voltages are within the secure operable range.

Table 3.1: Location and constraints of EVs in Scenario 1-b

Parameters and Results	
EV Capacity	40 kW
Available EVs	20
Total Capacity	800 kW
Location	Node 25
Load Shedding	Reduced by 510 kW (930 to 420 kW)
Load Pickup	Node 23 and Node 25

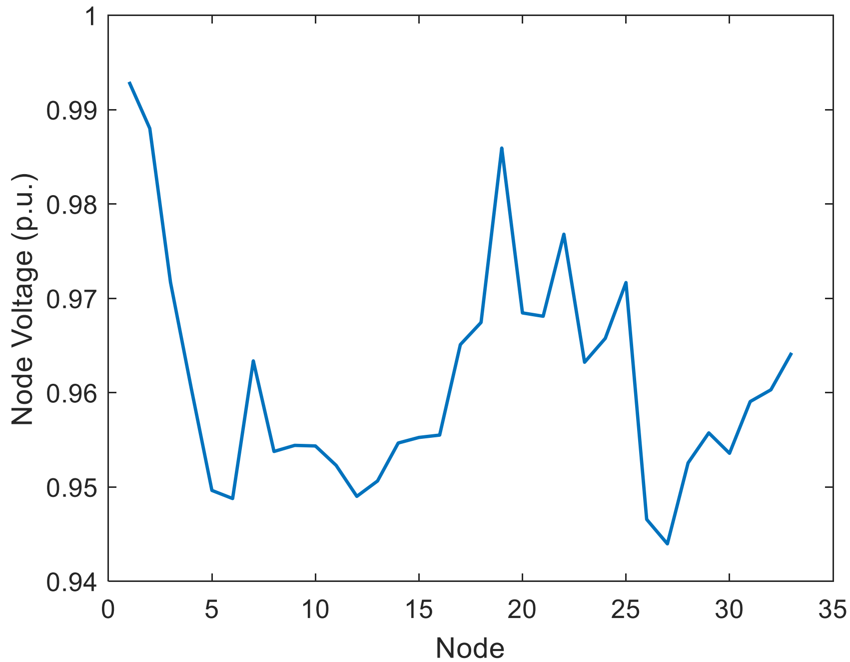

Figure 3.13: Voltage profile under Scenario 1-b

In Scenario 2-a, two distribution lines are tripped at the same time and the total load shedding is 1290 kW. In comparison, if EVs are optimally dispatched to pick up the loads, the total load shedding is reduced to 420 kW in Scenario 2-b. Among the 20 EVs, 8 EVs are dispatched to Node 20 and 12 EVs are dispatched to Node 25. The 8 EVs and 1 PV are able to supply power to pick up the loads on nodes 19-22. The 12 EVs will partially serve the load on feeder 23-25.

CHAPTER 4: CONCLUSIONS AND FUTURE WORK

This thesis develops optimization models to optimally utilize PVs and energy storage in the distribution power grid to improve the system operational efficiency and enhance the system resilience. A more sustainable energy system can be reached through improved resiliency efforts. This is the case when catastrophe events such as hurricanes or severe storms are experienced by a power grid system. A highly resilient power grid can bring the power supply back to customers within a short time period. This will minimize the potential for harm to those who are dependent on the grid itself. Through the proposed optimal operation model, the operation and scheduling of PVs and ES units are optimally dispatched in an efficient manner in order to fulfill the needs of the power grid. Meanwhile, no system operational constraints are violated at any of the buses. The optimal solution has been demonstrated to be beneficial to the power grid during both normal and contingency operational scenarios where the main generation source becomes hindered or inactive. Therefore, the utilization of PV systems as well energy storage units in the power grid can help improve system resiliency and overall efficiency when coordinated correctly.

In the future work, the following aspects should be investigated.

(1) In a disaster scenario, the occurrence of distribution line trips can be uncertain. We will incorporate the uncertainties of contingencies into the optimization models and utilize stochastic programming-based approaches to obtain an optimal solution that is robust to the uncertainties.

(2) The routing of EVs depends on the transportation network. We will model the transportation network and optimal routing model for EVs and integrate it into the proposed model in this work.

(3) We will utilize machine learning-based approaches to predict the impact of a disaster in terms of where and when the power grid will be interrupted. This kind of approach can also be used for the optimal control and dispatch of EVs in response to events/disasters and to enhance the grid resilience.

REFERENCES

[1] J. Kim and Y. Dvorkin, "Enhancing Distribution System Resilience With Mobile Energy Storage and Microgrids," in *IEEE Transactions on Smart Grid*, vol. 10, no. 5, pp. 4996-5006, Sept. 2019.

[2] B. Zhang, P. Dehghanian and M. Kezunovic, "Optimal Allocation of PV Generation and Battery Storage for Enhanced Resilience," in *IEEE Transactions on Smart Grid*, vol. 10, no. 1, pp. 535-545, Jan. 2019.

[3] The International Energy Agency. “Global EV Outlook 2019”, 2019. online: https://www.iea.org/publications/reports/globalevoutlook2019/

[4] M.Panteli, D.N.Trakas, P.Mancarella, andN.D.Hatziargyriou,“Power Systems Resilience Assessment: Hardening and Smart Operational Enhancement Strategies,” Proc. IEEE, vol. 105, no. 7, pp. 1202–1213, 2017.

[5] M. Panteli and P. Mancarella, “Operational resilience assessment of power systems under extreme weather and loading conditions,” in Proc. IEEE PES Gen. Meeting, Denver, CO, USA, 2015, pp. 1–5.

[6] E. Vugrin, A. Castillo, and C. Silva-Monroy, “Resilience metrics for the electric power system: A performance-based approach.” Sandia National Laboratories, Albuquerque, NM (United States), Tech. Rep., 2017.

[7] S. Neumayer and E. Modiano, “Assessing the effect of geographically correlated failures on interconnected power-communication networks,” in 2013 IEEE Int’l Conference on SmartGridComm,, 2013, pp. 366–371.

[8] K. Eshghi, B. K. Johnson, and C. G. Rieger, “Power system protection and resilient metrics,” in Proc. IEEE Resilience Week, Philadelphia, PA, USA, 2015, pp. 1–8.

[9] Y. Liu, Q. H. Wu, and X. X. Zhou, “Co-ordinated multiloop switching control of DFIG for resilience enhancement of wind power penetrated power systems,” IEEE Trans. Sustain. Energy, vol. 7, no. 3, pp. 1089–1099, Jul. 2016.

[10] T. C. Ly, J. N. Moura, and G. Velummylum, “Assessing the bulk power system’s resource resilience to future extreme winter weather events,” in Proc. IEEE Power Energy Soc. Gen. Meeting, Denver, CO, USA, 2015, pp. 1–4.

[11] W. Liu, L. Sun, Z. Lin, F. Wen, and Y. Xue, “Multi-objective restoration optimization of power systems with battery energy storage systems,” IET Gener. Transm. Distrib., vol. 10, no. 7, pp. 1749–1757, May 2016.

[12] Y. Sun, Z. Li, W. Tian, and M. Shahidehpour, “A Lagrangian Decomposition Approach to Energy Storage Transportation Scheduling in Power Systems,” IEEE Trans. Power Syst., vol. 31, no. 6, pp. 4348–4356, 2016.

[13] H. Gao, Y. Chen, S. Mei, S. Huang, and Y. Xu, “Resilience-oriented pre-hurricane resource allocation in distribution systems considering electric buses,” Proc. IEEE, vol. 105, no. 7, pp. 1214–1233, Jul. 2017. [Online]. Available: http://ieeexplore.ieee.org/stamp/ stamp.jsp?arnumber=7879853.

[14] M. A. Darfoun and M. E. El-Hawary, “Multi-objective optimization approach for optimal distributed generation sizing and placement,” Elect. Power Compon. Syst., vol. 43, no. 7, pp. 828–836, Apr. 2015.

[15] H. Pandži´c, Y. Wang, T. Qiu, Y. Dvorkin, and D. S. Kirschen, “Near optimal method for siting and sizing of distributed storage in a transmission network,” IEEE Trans. Power Syst., vol. 30, no. 5, pp. 2288–2300, Sep. 2015.

[16] B. Zhang, P. Dehghanian, and M. Kezunovic, “Optimal allocation of pv generation and battery storage for enhanced resilience,” IEEE Transactions on Smart Grid, 2017.

[17] Y. Wang, C. Chen, J. Wang, and R. Baldick, “Research on resilience of power systems under natural disasters review,” IEEE Transactions on Power Systems, vol. 31, no. 2, pp. 1604–1613, 2016.

[18] R. V. Zaitsev, M. V. Kirichenko, G. S. Khrypunov, D. S. Prokopenko and L. V. Zaitseva, "Development of hybrid solar generating module for high-efficiency solar

energy station," 2017 IEEE First Ukraine Conference on Electrical and Computer Engineering (UKRCON), Kiev, 2017, pp. 360-364.

[19] Taher, S. A., & Afsari, S. A. (2012). Optimal Location and Sizing of UPQC in Distribution Networks Using Differential Evolution Algorithm. *Mathematical Problems in Engineering*, 2012, 1–20. doi: 10.1155/2012/838629.

[20] S. Wang, S. Chen, L. Ge, L. Wu, “Distributed generation hosting capacity evaluation for distribution systems considering the robust optimal operation of OLTC and SVC”, IEEE Trans. Sustain. Energy, 2016, vol. 7, no. 3, pp. 1111-1123, 2016.