Birzeit University

Faculty of Engineering and Technology

Joint Master in Electrical Engineering (JMEE)

Optimal Operation of a Power Grid with High Penetration of RES and Storage Systems

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This Thesis was submitted in partial fulfillment of the requirements for the Master's Degree in Electrical Engineering from the Faculty of Engineering and Technology at Birzeit University, Palestine

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التشغيل الأمثل لشبكة الكهرباء مع وجود تكامل أنظمة الطاقة المتجددة وأنظمة التخزين

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Examination Committee

Dr. Abdalkarim Awad
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This thesis was prepared under the main supervisor Dr. Abdalkarim Awad and co-supervisor Dr.Muhammad Abu Khaizaran and has been approved by all members of the examination committee. The thesis defense date was on ……………….

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Declaration

I declare that this thesis entitled "Optimal Operation of a Power Grid with High Penetration of RES and Storage Systems" is the result of my own research except as cited in the references. It is being submitted to the Master's Degree in Electrical Engineering from the Faculty of Engineering and Technology at Birzeit University, Palestine. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Name: ………………………………

Signature: ………………………………….

Date: ……………………………………

Acknowledgement

To my Mother, Father, Wife, Children, to

Abdalkarim Awad and Muhammad Abu Khaizaran

and finally to OOREDOO Company

Abstract

The future power grid is characterized by a high penetration of Renewable Energy Sources (RES), storage elements and extensive usage of information and communication technologies. Although the RES have positive environmental and economic impact on the power grid, the intermittent nature of such sources present new challenges to the future power grid, these new challenges may affect users and power grid infrastructure itself, such as losses, over voltages, protection and frequency. Furthermore, storage elements such as Electric Vehicles (EV) present additional load in the power grid. Yet, the EVs can be exploited to store energy when the supply energy is higher than the demand's, and then to provide energy to the grid when it is needed, this solution may increase willing to have this types of cars if the cost of energy selling was attractive. Unbalanced system voltage is one of the grid problems, which is not easily controlled, since the voltage magnitude is affected by the load. RES and storage system could be used to keep the voltage within a band accepted by various regulatory standards. In this work, a nonlinear programming model is proposed to optimally operate a power system, which contains RES and storage elements. Additionally, simulation tools are used to explore and solve different scenarios.

المستخلص

تتميز شبكة الطاقة المستقبلية بتغلغل كبير في مصادر الطاقة المتجددة وعناصر التخزين والاستخدام المكثف لتكنولوجيا المعلومات والاتصالات. على الرغم من أن مصادر الطاقة المتجددة لها تأثير بيئي واقتصادي إيجابي على شبكة الطاقة ، إلا أن الطبيعة المتقطعة لهذه المصادر تمثل تحديات جديدة لشبكة الطاقة المستقبلية ، قد تؤثر هذه التحديات الجديدة على المستخدمين والبنية التحتية لشبكة الطاقة نفسها ، مثل الخسائر في خطوط النقل، ازدياد في قيمة الفولتية ، الحماية و التردد. علاوة على ذلك ، فإن عناصر التخزين مثل المركبات الكهربائية تقدم حمولة إضافية في شبكة الطاقة. ومع ذلك ، يمكن استغلال السيارات الكهربائية لتخزين الطاقة عندما تكون طاقة التزويد أعلى من الطلب ، ومن ثم توفير الطاقة للشبكة عند الحاجة ، قد يلاقي هذا الحل استحساناً لاستخدام هذه الأنواع من السيارات إذا كانت تكلفة الطاقة المباعة جذابا. يعد جهد النظام غير المتوازن أحد مشكلات الشبكة ، التي لا يمكن التحكم فيها بسهولة ، نظرًا لأن حجم الجهد يتأثر بالحمل. يمكن استخدام مصادر الطاقة المتجددة ونظام التخزين للحفاظ على الجهد داخل نطاق مقبول من قبل المعايير التنظيمية المختلفة. هذا العمل يقترح نموذج برمجة غير خطي لتشغيل نظام الطاقة على النحو الأمثل ، والذي يحتوي على مصادر الطاقة المتجددة وعناصر التخزين. بالإضافة إلى ذلك ، يتم استخدام أدوات المحاكاة لاستكشاف وحل السيناريوهات المختلفة.

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Acronyms and Abbreviations

BEV	Battery Electric Vehicles
CESS	Community Energy Storage Systems
CHP	Combined Heat Plant
DER	Distributed Energy Sources
DG	Distributed Generator
EL	Elastic Loads
ESS	Energy Storage System
EV	Electric Vehicles
G2V	Grid to Vehicles
GAMS	General Algebraic Modeling System
ICE	Internal Combustion Engine
IEC	International Electrotechnical Commission
NEMA	National Electrical Manufacturers Association
NLP	Non Linear Programming
OCV	Open Circuit Voltage
OLTC	On-Load Tap Changer
OPF	Optimal Power Flow
PHEV	Plug-in Hybrid Electric Vehicles
PV	Photovoltaics
PVUR	Phase Voltage Unbalance Rate
RES	Renewable Energy Sources
SOC	State of Charge
SOH	State of Health
V2G	Vehicles to Grid

Chapter 1

Introduction

1.1 Background

Specialists from academia and industry generally agree on that, the utilization of Renewable Energy Sources (RES) is an important way to reduce the emissions produced by the conventional power plants. Therefore, in the last decade, diverse forms of small distributed generators, such as solar power plants, wind power plants and combined heat plants (CHP), have been connected to the electricity distribution networks. An important driver for the large installations of the Distribution Energy Resources (DER) is the technological advances in this field.

The main objectives of integrating the renewable energy sources with the electricity network are:

1- Environmental: reducing the CO2 emotion
2- Economical: reducing the capital cost and operational cost of the energy sources upgrade

Unfortunately, high penetration of renewable energy has a severe impact on the existing grid, and may affect the consumers in case the produced energy is larger than consumed, an overvoltage may occur. Another important element of future power grid is the energy storage systems. These can be static storage units, such as

Community Energy Storage Systems (CESS), or mobile such as Electric Vehicles (EV) [1].

The integration of the RES in the power grid will be made possible not only by the price-performance revolution of microelectronics, but also by the development of efficient algorithms that are able to deal with the special characteristics of the Distributed Energy Sources (DER) such as the output power fluctuations due to environment and sizes of these DER. In this work, algorithms will be developed to optimally coordinate the different components of future power grid such as RES and Storage System. Because real implementation of a power grid is expensive and maybe impossible, different simulation tools will be used, such as OpenDSS and GAMS [2]-[3].

The distribution of the electric vehicles worldwide provides a good opportunity to be used in the distribution network as a storage energy element by using a bi-directional power electronics circuit G2V (Grid to Vehicles) and V2G (Vehicles to Grid). A study conducted by Bloomberg New Energy Finance shows that the price of EVs will be cheaper than conventional internal combustion engine (ICE) vehicles by mid of 2020s, as can be seen in Figure (1.1).

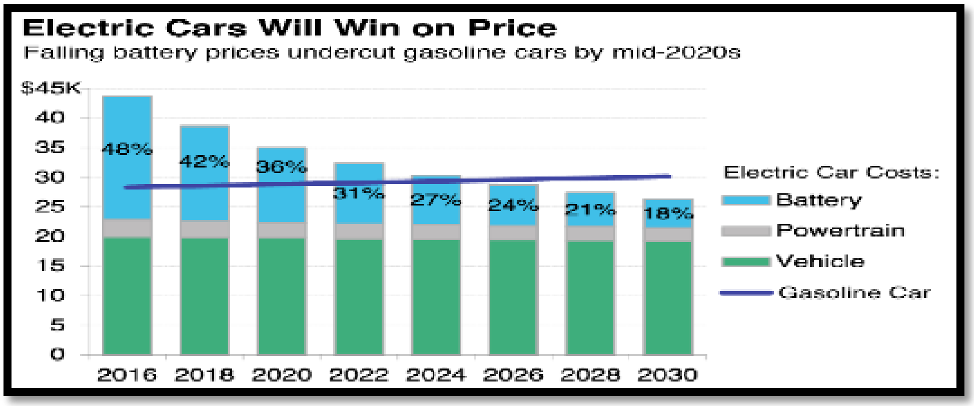


Figure 1. 1: The Evolution of EVs prices during the next decade [4]

This will advance the penetration of EVs in the market, which may have positive impact on the grid if used smartly. EV charging is done by an onboard charger, which may last for hours. But, using fast chargers will reduce the charging time to around one hour [4].

The EV user driving behavior and his/her willingness to plug the EV into the grid are the most important factor to enable the provision of power system services from EVs, so the price of electricity provided by the EVs (V2G) should be encouraging to motivate customer.

The most commonly used battery in EV implements Li-ion technology, since this technology shows a greater energy capacity with respect to weight, low self-discharge and the estimation of SOC for this technology is easier than others as well. On the other hand, the price of this type of battery per kWh is reduced to 1/5 in the last 7 years, as shown in Figure (1.2).

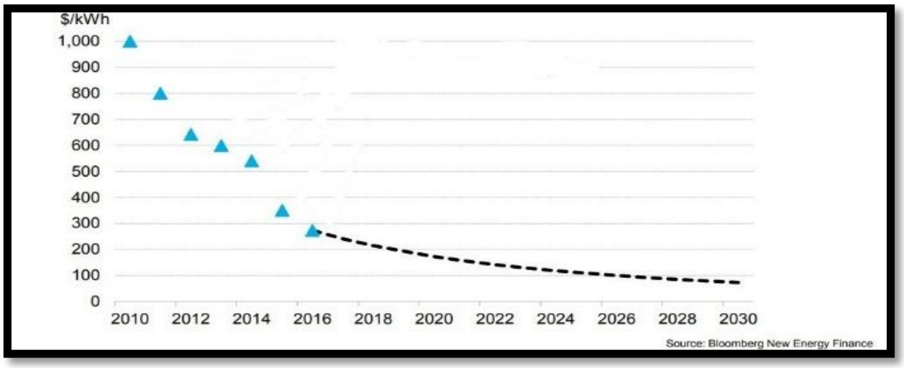


Figure 1. 2: The price of Li-Ion battery [4]

1.2 Problem Statement

High penetration level of RES is the target of most of the electricity providers due to economic and environmental savings. But, the fluctuations of RES will impact the operation of the electric grid. These fluctuations create problems in the grid operation such as overvoltage and supply/demand mismatch. To solve this issue a controller could be implemented to optimally coordinate the operation of the different components of the grid; e.g., to inject or consume a reactive power, control the charge/discharge of energy storage system (ESS) and the running time of elastic loads (EL). On the other hand, most of the residential loads are connected to single and three phase distribution transformers, which may produce phase imbalance, that could be resolved by the controller.

The main goal of this work is to implement a simulation model of a power gird with RES and ESS. Then some scenarios and possible services, provided by the different components (e.g., reactive power compensation), will be explored. Afterwards, nonlinear optimization problem will be modeled and solved. The OpenDSS simulator will be used for the implementation. General Algebraic Modeling System (GAMS) will be used to describe the optimization problem that will be solved by an external solver.

1.3 Objectives

The main objectives of this study are below:

1- Reduce transmission line losses
2- Enhance the three phase balance of the system
3- Keep the three phase voltages range within the acceptable values
4- Maximize the output energy from the RES

1.4 Thesis Layout

This Thesis is organized in six Chapters where, Chapter two presents an overview of the RES, discusses the benefits of Storage System and investigates a literature review for Optimization problems, Unbalance system voltages and Line losses, Chapter three presents the used Tools for this simulations, Chapter four demonstrates the System Algorithm and Mathematical models, Chapter five discusses the Simulation and Results and Chapter six shows the Conclusion and Future works.

Chapter 2 Literature Review

2.1 Renewable Energy

Every day, the sun delivers energy to the earth free of charge. Users can use this free energy, thanks to a technology called photovoltaics, which converts the sun's energy into electricity. Photovoltaic modules or panels are made of semiconductors, that allow sunlight to be converted directly into electricity. These modules can provide a safe, reliable, maintenance-free and environmentally friendly source of power for a very long time. Most modules on the market today come with warranties exceeding 20 years, and will perform much longer [5]. Forecasting also shows a great potential of the Photovoltaics to be the green power sources of the future, because of many merits they have (such as high efficiency, zero or low emission of pollutant gases, and flexible modular structure) and the rapid progress in these technologies [6]. However, each of the aforementioned technologies has its own drawbacks. This work will discuss the impact of connecting the PV system to the grid, the main advantages of the PV system on the grid are the enhancement of the voltage profile and reduction of the feeder losses. On the other hand, connecting this system to the grid with a high penetration level will produce harmonics and high voltage on the buses in case the load demand is less than the produced energy.

Fortunately, the customers can use this energy to reduce consumption from the utilities and will help in saving the planet by reducing CO2 emission, especially that the price of PV modules is dramatically decreasing day by day, as shown in Figure (2.1); the price for 1 W becomes less than half a US Dollar.

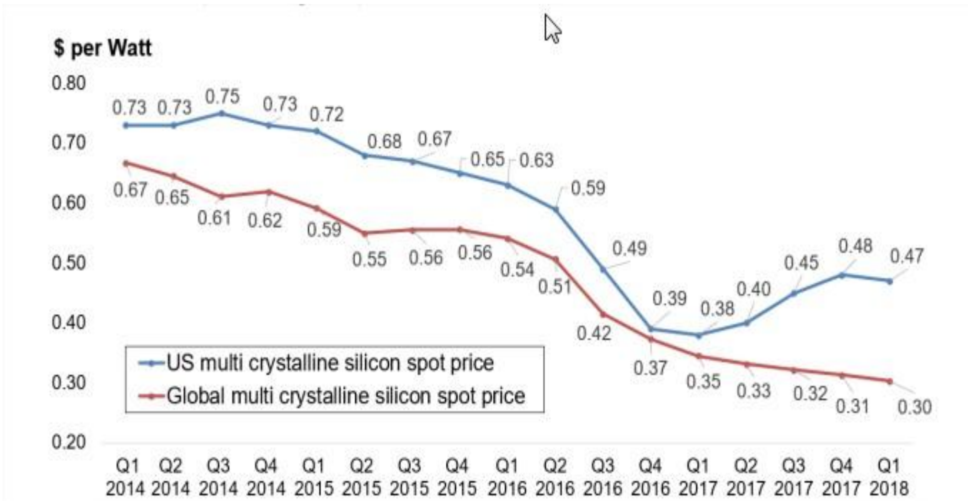


Figure 2. 1 : The price of the silicon PV Modules[7]

On the other hand, wind energy is used as renewable energy before solar energy and it became popular in recent years, as shown in Figure (2.2). Unpredictable forecast of this technology is one of its main drawbacks. The installed wind power capacity in Europe for 2018 are 9016 MW, while the installed solar power capacity is 6,112.8 MWp [8].

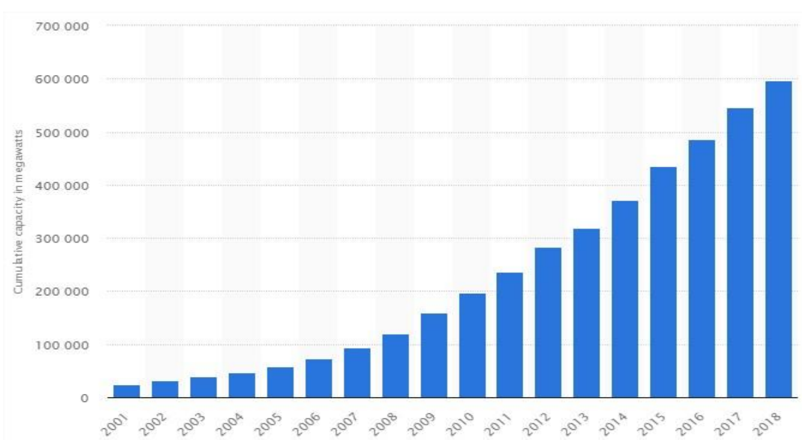


Figure 2. 2 : Cumulative installed capacity of wind power [9]

For example, in Germany, it is noticeable that the wind power capacity is larger due to the availability of wind over the day and year, as listed in Figure (2.3). The percentage of installed renewable energy sources penetration in Germany, as an example from Europe region, is about 30%, which is very high with respect to other countries [10].

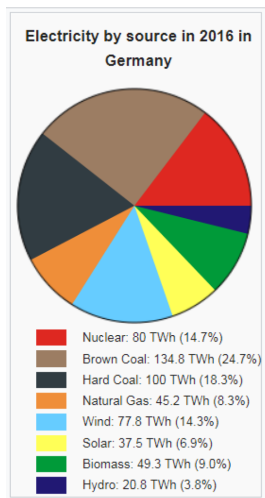


Figure 2. 3 : Electricity by Source in Germany in 2016 [10]

The renewable energy sources are a good solution to fill the gap of demand, but unfortunately, maximizing the integration of renewable energy sources introduces new challenges due to [11]:

a. High voltage at the buses at light load

b. Supply/Demand mismatch

c. High harmonic distortion due to power electronic devices

d. Additional power flows in the transmission system: Reverse power flows can cause additional power flows from the distribution system to the transmission system
e. Grid stability: frequency and voltage

The integration of the RES in the power grid will be made possible not only by the price-performance revolution of microelectronics, but also by the development of efficient algorithms that are able to deal with the special characteristics of the DER such as the output power fluctuations and sizes. In this thesis, algorithms will be optimized to coordinate the different components of future power grid.

2.2 Storage System

The generated electricity is consumed by the load at the same time of generation, so the generation shall always meet the load demand to satisfy the customer. But the increase in demand may lead to instability in electricity. In general, the electrical generators are located far from the load and are connected via transmission lines, which means that huge transmission losses will be encountered in the case of increased in demand. Since the prices of electricity vary throughout the day due to demand; on the off-peak hours, the price is low, whilst its high during peak hours [12].

The high penetration in RES produces surplus energy especially during the off-peak hours. This surplus energy could be stored in a storage system to be used again during the peak hours. Since, the price of electricity vary the customers may charge their EV batteries at low prices during off-peak, and sell the electricity to the utility during the peak hours, but at higher prices. However, the life cycle of EV batteries must be taken into consideration.

The storage system may be classified into three types:

1- Mechanical Storage system

   a. Flywheel: is a mechanical storage which stores kinetic energy in rotational rotor and coupled with electric generator and the rotational part releases when needed [13].
   b. Pumped hydroelectricity: is a mechanical storage technique, when the demand is low the water is pumped to high place and released when the demand increased to regenerate electrical energy again [14].
   c. Compressed Air Pump: is mechanical storage techniques, when the demand is low the energy stored in compressed air and released when the demand increases [15].

2- Electrochemical

a. Battery: is an electrochemical storage device where energy is stored as chemical and reused when needed, there are many types of this battery as lithium and lead acid [16].

b. Fuel Cell: it is an electrochemical storage device that convert Hydrogen to electricity energy [17].

3- Electrical

a. Super Capacitor: is an electrical storage device it's structure same as capacitor but the area is higher and thinner electrode which increase stored energy [18].

b. Superconducting magnetic coil: it is an electrical technique to store current in a large magnetic coil [19]

The most popular type and widely used is lead acid battery system, where the battery is used in mobile, emergency light, cars …. etc. It is noticeable that, it is used as an emergency standby system because it is small and has a low cost when compared with other types. This type of battery has lifecycle which is reduced with number of discharge/charge, also the efficiency of the battery goes down if it is deeply discharged with high power. The life time of battery goes down rapidly in deep discharge cases. The gauge meters of the battery are the State of Charge (SOC) and State of Health (SOH). SOC indicates the stored energy in the battery, when SOC is 100% it is full and empty at 0%. The estimation of SOC is regularly measured by Coulomb counting method, but this method doesn’t reflect the impact of aging, internal cells temperature and different leakage current, M.Quran in [20], merge four techniques to get more accurate SOC estimation, by reading OCV of the battery, battery currents with Coulomb efficiency factor and rated capacity of the cell in addition to Coulomb counting method. SOH indicates the health of battery with respect to ideal conditions, it could be estimated by following methods:

1- Chemical [21]

2- Voltage [22]

3- Current Integration [23]

4- Kalman Filtering [24]

The most commonly used method is the voltage. The voltage shows the percentage of the stored energy with the dropped current, but the characteristic of discharge curve must be known.

One of the modern energy storage systems is the Electric Vehicles (EV), Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs), which are becoming more popular. PHEVs are charged by plugging them in to the grid or by another generator source. Charging these vehicles has an enormous impact on the grid since they consume a huge power, especially when charging a lot vehicle simultaneously, leading to undesirable peak power consumption. On the other hand, the EV could be used as an energy source and inject power back to the grid. To maximize the benefits of using EVs, the users need to charge the batteries, without affecting cells, and to discharge them, selling energy to the utilities, with a maximum price. Lopez *et al.* in [25] proposes an algorithm to maximize the income of the EV users from selling the energy to utilities, the objective function is related to the state of charge of the EV's, voltage limits and power flow constraint due to transmission and losses. The researchers also looked for another way to inject the reactive power or consume it in the distribution network, the source for this is the batteries in the electric vehicles. Thanks to power electronics that made the conversion of the energy G2V and V2G is available. According to power electronics efficiency for optimizing the energy loss of a microgrid with different penetration levels of PHEVs and its effect on the batteries, a two-stage method for solving this issue is presented, and the results show that reactive power didn't affect the batteries' lifetime and SOC [26]. Now for integration of the Plug in Electric Vehicles with the grid, reference [27] discussed coupled energy and reactive power market in the presence of reactive power, the objective function structure for three-stage energy cost, total payment for reactive power and lost opportunity cost all of these to be minimized, this case is studied on IEEE 134 for two cases with and without PEV penetration, the result shows that the independent system operator payment is greater in the case of the payment without PEVs in the market.

Regarding the impact of the electric vehicles, reference [28] discussed Monte Carlo to address the uncertainties associated with wind speed variation and charging of PEVs. A lot of scenarios were studied with different penetration level from the DG and the PEV and applied on IEEE-123 bus. The result shows that, 30% of DER are enough to supply active energy to the PEV. Since the EV is a load and a source for the network, but it is usually load, Andres [29] used escort evolutionary game dynamics as a tool for the distributed integral load management of PEVs. The developed scheme is flexible and allows PEVs to work together in a fair scheme, in order to balance the active load power, and partially fulfill the reactive power demand of each phase of the transformer.

On the other hand, managing the energy stored in the batteries introduces an optimization and control framework that can be used for charging batteries and managing available storage, while using the remaining capacity of the chargers to generate reactive power and cooperatively perform voltage control [30]. The optimization scheme was based on two-stage instantaneous power/voltage control and power control. The results show a tool to manage storage, renewable distributed generation, and demand response. Wenxi *et al.* in [31] proposed a coordination optimization of battery storage system between active and reactive power, with the goal of realizing lowest power loss as well as minimal voltage fluctuations in active power network. The case study demonstrated that, through coordinated control of active and reactive power of battery energy storage. Power loss in active distribution network can be decreased more remarkably compared with that when active power of battery energy storage is dispatched only.

2.3 Optimization Problem

The modeling for finding the best solution for a problem is called optimization. In this case, the optimization solver will be used to find the best solution to operate or merge the electrical supplier component to get the best profit and minimal transmission losses. Usually, an optimization problem has more than one solution each time period, which is logical for this case, since the energy production and demand varies with environment and users. In order to implement an optimization problem for energy sources the following points must be available [32]:

1- Electricity price day ahead
2- Prediction of PV energy production
3- Prediction of demand

The main idea is to define the best strategy to maximize the profit of the renewable energy sources, to decrease the transmission losses and to increase lifetime for storage and OLTC transformer, all this could be implemented if the cost for each one is defined.

Another approach to implement optimization quickly is by doing a rule based algorithm. This is called a logic programming with control. As an example of this type is maintaining the voltage within an acceptable range, the voltage boundaries will be defined, and a control will be applied to the system in the function below:

Rule Based Algorithm to Control Voltage

1- ***if*** $V_{min} > V_{bus}$
2- Discharge Storage System
3- ***Else***
4- Charge Storage System
5- ***End***

The difference between the two optimization types is that, the rule based is faster but does not optimize the lifecycle of the storage system and does not consider the operation price, it may be helpful to cover the demand in some cases [33].

As illustrated before, the main objective of the optimal power flow (OPF) is to maximize the integration of the RES and ESS to the network and minimize the generation and transmission losses. Distributed multi – period OPF for a distribution grid system with PV system integrated with smart inverter and energy storage is presented in [34], The main objective was to keep the voltage across the grid within acceptable range with maximization the RES penetration.

In [35] a simulation for a micro grid with four conventional generators including the generator cost, weather condition and state of charge (SOC) for batteries, the optimal power flow is to minimize the fuel and cost of switching of the generator and the cost of not producing power if ESS is full. Due to connecting more than one distributed generator may enhance voltage regulation but it’s also increase in voltage fluctuation over the different busses, OLTC is one of the solutions to control the voltage regulations but the main drawback is the number of operation which affect lifetime of the transformer, [36] propose a technique to optimize number of tap operations which increase lifetime cycle of the transformer. Mahmud *et al*, in [37] proposed a solution to control the voltage across the feeders by getting a real time data from the bus, user and storage system, the voltage is controlled by changing the taps of the transformer or by connecting/disconnecting the renewable or storage system to/from the bus. In [38] the coordination between the PV station and high-voltage/medium-voltage substation OLTC settings is the proposed strategy to control voltage regulation, the used simulator is OpenDSS, the result shows that the impact of temperature and irradiance which may affect the reactive power generation from PV system is minimized after coordination with OLTC settings. One of the methods used to regulate voltage is the voltage controlled demand response, and OLTC is an old technique for that, but the operations of OLTC may affect system frequency stability, [39] propose a novel approach by design an adaptive supervisory controller, which aim to study the effect of OLTC operations on system frequency on IEEE-39 test bus, the result shows that by optimizing OLTC operations maximize steady system frequency stability and reduce number of tap operations.

2.4 Reactive Power

To cover the needed demand, the utilities usually connect new generator to the grid. This operation is costly and needs time to cover the load especially if the increase in the load exist for a short period of time. Nowadays, implementation of a new power plant driven by fossil fuel is also costly and affect the environment. Thus, the utilities want to cover the demand by other solutions such as encouraging customers to distribute the load by kWh price. This case is not valid all the time, but reduces the output apparent power from the generators. As known, the components of apparent power in a power grid is real and reactive, a higher reactive power leads to less system efficiency, a lower power factor and higher line losses. The utilities use techniques to compensate the reactive power by capacitor banks, and recently power electronics converters such as STATCOM.

Volt-VAR control is one of the technical solutions to reduce power consumption at the end user as explored and simulated in [40]. Turitsyn, et al. in [41] propose a control scheme to inject a reactive power from the PV inverter. This control scheme could be tuned to robust the voltage control during daytime operation and minimize the losses for nighttime operation. The work in [42] proposes a combined problem formulation for active and reactive optimal power flow in the distribution generator with embedded wind generation and battery storage. This solution was applied on 41-bus. The energy losses were reduced by 12% from the transmission networks, in addition to importing a reactive power from the networks when active power is considered only. The research in [43] focuses on the design and implementation of two controllers for a photovoltaic inverter for rooftop system. The first controller aims to eliminate the voltage violation and to keep the voltage within the acceptable range. The second controller was implemented to reduce the energy losses in the distribution network and reactive power in the substations. The results show that, the controller is able to substantially reduce real energy losses in the feeder and reactive energy demand at the substation. Besides, it is obvious that, reducing reactive demand at the substation leads to heat loss reduction of substation transformer and transmission network.

2.5 Unbalance System

The three phase system with four wire configuration (3 phase + neutral) is built to be balanced as the magnitude for all phases are equal, but the phase shift between them is + 120 and -120 degree. The unbalance in three phase system happen since single phase loads are distributed unevenly or switched on/off unpredictably or due to blown fuses in capacitor bank …. etc. So the user will not get a pure balanced three phase. The type of unbalanced system can be classified into two types:

1- Unbalanced Under Voltage
   a. One phase under voltage
   b. Two phase under voltage
   c. Three phase under voltage
2- Unbalanced Over Voltage
   a. One phase over voltage
   b. Two phase over voltage
   c. Three phase over voltage

The effect of unbalanced system, mainly on the industrial plants, in particular motors' applications, is sever where unbalanced voltage will [44] increase stator temperature, especially when the unbalanced system is experiencing under voltage condition.

Most of residential solar system are grid connected, and most loads are single phase. So the possibility for unbalance voltage increases. This thesis aims to keep the voltage within a balanced threshold based on the definition of balanced voltage in IEEE, where voltage unbalance is the maximum deviation to the average value of three phases. The definition of NEMA is similar to IEEE definition, but they use line voltage, while IEC definition is the ratio between negative sequence to the positive sequence [45].

2.6 Line Losses

One of the factor that increase generation is the line losses of the transmission lines, there are two type of these losses, the first one is the real and the second is the reactive losses, the losses depend on the characteristic of the lines and the flowing current, existing of the DG may reduce or increase losses depend on the location of the DG, [46]-[48] discuss the impact of the location of DG and the line losses, the result shows that the location of DG may reduce the line losses depends on the distance of the load and DG. Zeb *et al,* in [49] propose a practical swarm optimization algorithm to optimally locate DG to decrease line losses and enhance voltage profile, the location of DG in some cases increase line losses and doesn't improve voltage profile. The growing interest in use of EV has been increased last decade, the charging of EV increases power flow in the transmission lines which accordingly increase line losses, but considering EV as storage system will add flexibility to the grid operations, the power electronics converter allows the power flow near to the charger be bidirectional V2G and G2V [50].

Chapter 3 Tools

Various simulation tools will be used to achieve the objectives of this thesis. These tools are:

a- OpenDSS:

The Open Distribution System Simulator (OpenDSS, or simply, DSS) is a comprehensive electrical system simulation tool for electric utility distribution systems. OpenDSS refers to the open source implementation of the DSS. It is implemented as both a stand-alone executable program, and an in-process COM server DLL designed to be driven from a variety of existing software platforms. The executable version has a basic text-based user interface on the solution engine to assist users in developing scripts and viewing solutions. The program supports nearly all RMS steady-state (i.e., frequency domain) analyses commonly performed for utility distribution systems planning and analysis. In addition, in OpenDSS it's easy to convert data sources to OpenDSS script. The scripting language was designed to be reasonably close to common text data formats used in distribution system analysis tools. The program was developed for a consulting and research environment in which model data is received from utilities in a variety of formats. Since OpenDSS can model transmission networks as well as distribution circuit, data for a single model often come from more than one source [2]. All the used models will be described as below:

Transformer:

The distribution transformer is usually used to step down the voltage from medium to low. In this thesis, a stepdown transformer from 33 kV to 0.4 kV and with DELTA to WYE connection is used. The rating of transformer is 630 kVA, and its model is as shown in Figure (3.1).

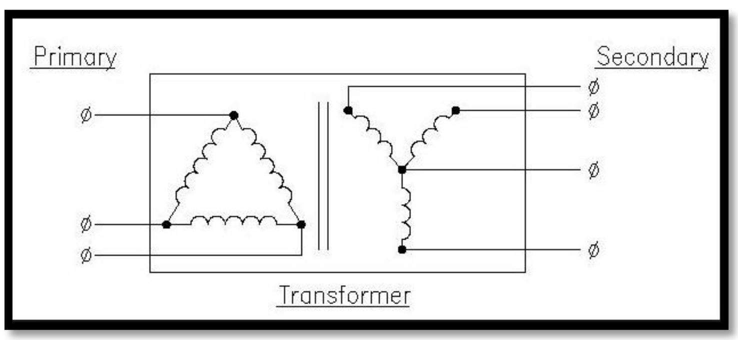


Figure 3. 1: Transformer Model in OpenDSS

Transmission Line:

The electrical energy is transferred from the transformer to the load by electrical cables. Most of distribution cables/overhead lines nowadays are Aluminum. The internal resistance of the cable/overhead line is the main cause of power losses, where the losses are expressed by equation (1).

$$P = 3I^2R \tag{1}$$

where,

I	line current.
R	Internal resistance of the cable.

Also, a sinusoidal current produces a sinusoidal varying flux which varies in the phase with the current. Accordingly, the transmission line characteristics are the resistance and inductance whose values are 0.32 and 0.075 Ω/km, respectively, these values are from the installed cables in Birzeit Neighborhood.

PV System:

Photovoltaic energy system, detailed in Figure (3.2), is modeled in OpenDSS with the following parameters:

Rating	kVA
Phases	Number 1, 2 and 3
Irradiance	Radiation shape in kW/m^2
P_{mpp}	Rated maximum power for irradiance

PF	Power Factor of the inverter
Temperature	Ambient Temperature

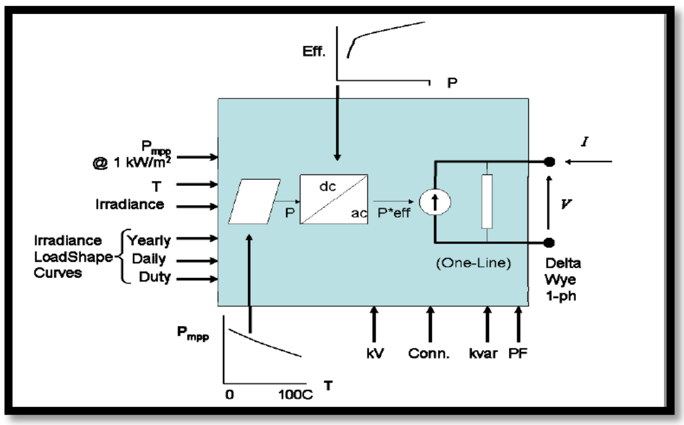


Figure 3. 2: PV Model in OpenDSS.

The interface of this model is as any other element in the network. It could be defined as a new element connected to the defined bus. The output power depends on the irradiance, temperature and rating of the PV system, while the reactive power could be defined by the power factor (PF) or by a determined value. The software will try to keep this reactive power value out/in of the inverter. Regarding the maximum power point tracker, the software assumes that the inverter can achieve operation at the maximum power point. The applied radiation shape is assumed to be have trend as in Figure (3.3), this shape is the average of one month in winter season from Birzeit University.

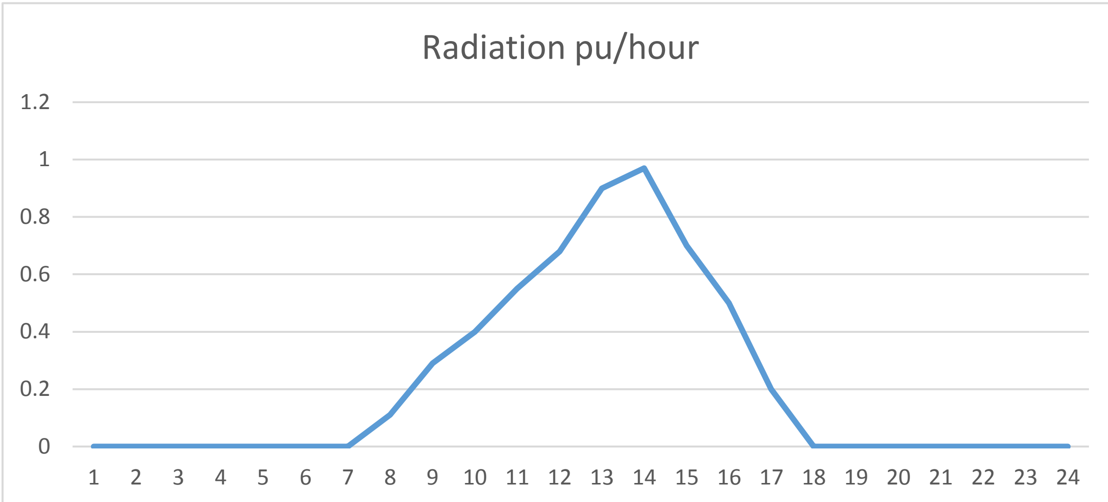


Figure 3. 3 : Radiation Shape

Storage Element:

Similar to the PV system, it is an element that can be connected to a bus, this model depends on a predefined parameter as below:

Rating	kVA
Phases	Number 1, 2 and 3
kW	Output power from the storage device
kW_{rated}	Rated output power
PF	Power Factor of the inverter
kWh_{rated}	Rated storage capacity in Wh

kWh_{stored} Stored energy

In this thesis, the electric vehicle is used as a storage system, and the rating for this EV is 10 kW and the battery rated capacity is 20 kWh, where these values are suggested for this case of study.

b- GAMS:

The General Algebraic Modeling System (GAMS) is a high-level modeling system for mathematical programming and optimization. It consists of a language compiler and a stable of integrated high-performance solvers. GAMS is tailored for complex, large scale modeling applications, and allows building large maintainable models that can be adapted quickly to new situations. GAMS is specifically designed for modeling linear, nonlinear and mixed integer optimization problems and is highly extensible. It compiles and runs on a wide variety of UNIX platforms and similar systems (including FreeBSD and Linux), Windows and MacOS.

Gams is an integrated suite of software facilities for data manipulation and calculations. It includes:

- An effective data handling and storage facility
- A suite of operators for calculations on arrays, in particular matrices

- A large, coherent, and integrated collection of intermediate tools for data analysis
- A well-developed, simple and effective programming language, which includes conditionals, loops, user-defined recursive functions and input and output facilities

The term “environment” is intended to characterize a fully planned and coherent system, rather than an incremental accretion of very specific and inflexible tools [2].

Chapter 4 System Algorithm & Mathematical Model

4.1 System Algorithm

The overall system diagram is detailed in Figure (4.1); where the blue lines represents the three phase voltage lines, the red lines are the control channels from controller to the inverters and the dashed green line for the communication channel between all the connected elements.

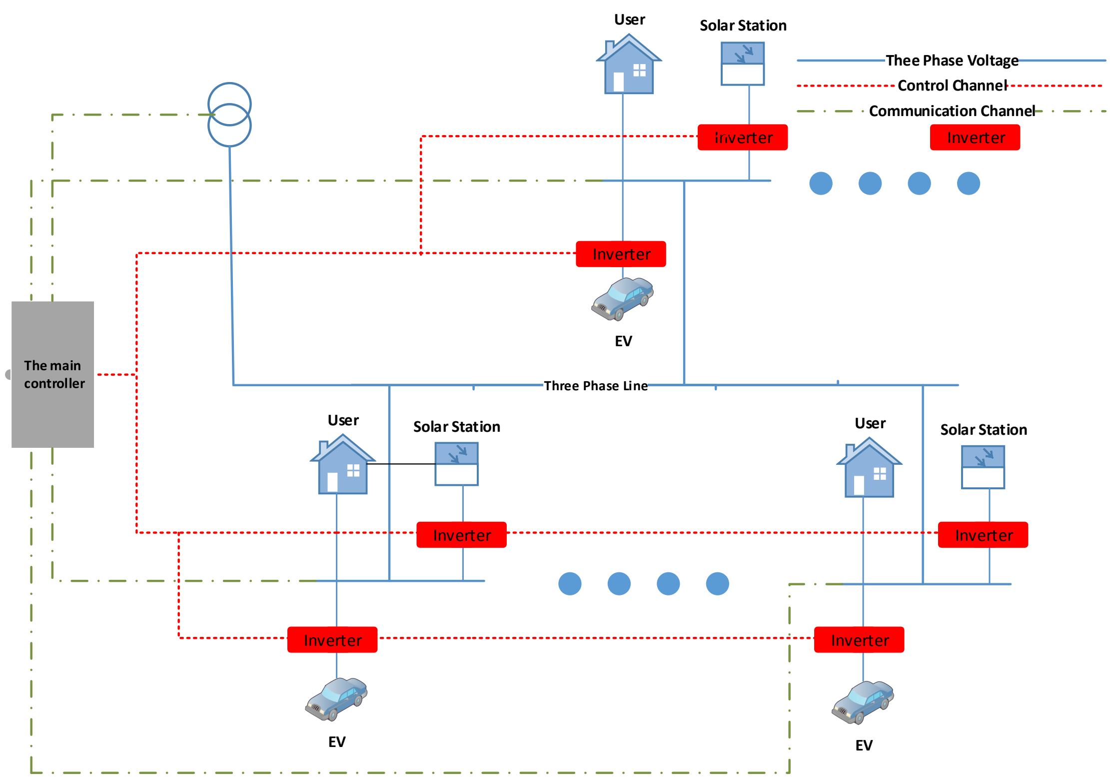


Figure 4. 1: System Overview

4.2 Mathematical Model

The components of an electrical power system are very large and need to be modeled in a way to study all the cases; such as fault case analysis, load flow… etc. A simulation tools built to do this is based on a lot of mathematical models for these components. The most important model in this work is the load flow equations, since the power flows from the source to the load [12].

$$S_{i,a,b,c} = P_{i,a,b,c} + jQ_{i,a,b,c} = VI^* \quad , for\ bus \tag{2}$$

$$I = \sum_{k=1}^{NB} Y_{ik} V_k \tag{3}$$

Substituting (2) in (3) yields the load flow equations:

$$P_{gen,a} + P_{pv.a} + P_{discharge.a} - P_{charge.a} - P_{load,a} = \sum_{k=1}^{NB} V_{i,a} * V_{k,a}[G_{ik}\cos(\delta_{i,a} - \delta_{K,a}) + B_{ik}\sin(\delta_{i,a} - \delta_{K,a})]; \tag{4}$$

$$P_{gen,b} + P_{pv.b} + P_{discharge.b} - P_{charge.b} - P_{load,b} = \sum_{k=1}^{NB} V_{i,b} * V_{k,b}[G_{ik}\cos(\delta_{i,b} - \delta_{K,b}) + B_{ik}\sin(\delta_{i,b} - \delta_{K,b})]; \tag{5}$$

$$P_{gen,c} + P_{pv.c} + P_{discharge.c} - P_{charge.c} - P_{load,c} = \sum_{k=1}^{NB} V_{i,c} * V_{k,c}[G_{ik}\cos(\delta_{i,c} - \delta_{K,c}) + B_{ik}\sin(\delta_{i,c} - \delta_{K,c})]; \tag{6}$$

$$Q_{gen,a} + Q_{pv,a} - Q_{Load,a} = \sum_{k=1}^{NB} V_{i,a} * V_{k,a}[G_{ik}\sin(\delta_{i,a} - \delta_{K,a}) - B_{ik}\cos(\delta_{i,a} - \delta_{K,a})]; \tag{7}$$

$$Q_{gen,b} + Q_{pv,b} - Q_{Load,b} = \sum_{k=1}^{NB} V_{i,b} * V_{k,b}[G_{ik}\sin(\delta_{i,b} - \delta_{K,b}) - B_{ik}\cos(\delta_{i,b} - \delta_{K,b})]; \tag{8}$$

$$Q_{gen,c} + Q_{pv,c} - Q_{Load,c} = \sum_{k=1}^{NB} V_{i,c} * V_{k,c}[G_{ik}\sin(\delta_{i,c} - \delta_{K,c}) - B_{ik}\cos(\delta_{i,c} - \delta_{K,c})]; \tag{9}$$

where,

$P_{gen,a,b,c}$	The real output power from transformer for each phase
$P_{load,a,b,c}$	Real power load for each phase

$P_{pv,a,b,c}$	The output power from RES for each phase
$P_{charge,a,b,c}$	The input power to EV for each phase
$P_{discharge,a,b,c}$	The output power from EV for each phase
$Q_{gen,a,b,c}$	The generated reactive power from Transformer
$Q_{load,a,b,c}$	The load reactive power
$Q_{pv,a,b,c}$	The generated reactive power from RES for each phase

G_{ik} and B_{ik} are the real and imaginary admittances, $\delta_{i,a,b,c}$ and $\delta_{k,a,b,c}$ are the angle between the buses for each phase. The mathematical model for power losses in the transmission lines is illustrated by equations (10) - (13) for each phase based on the real admittance of the transmission lines [40]:

$$Losses_a = \frac{1}{2}\sum_{n=1}^{N}\sum_{m=1}^{N} G_{ik}(\, {V_{a,n}}^2 + {V_{a,m}}^2 - 2\, V_{a,n}\, V_{a,m} \cos\theta_{a,nm}) \tag{10}$$

$$Losses_b = \frac{1}{2}\sum_{n=1}^{N}\sum_{m=1}^{N} G_{ik}(\, {V_{b,n}}^2 + {V_{b,m}}^2 - 2\, V_{b,n}\, V_{b,m} \cos\theta_{b,nm}) \tag{11}$$

$$Losses_c = \frac{1}{2}\sum_{n=1}^{N}\sum_{m=1}^{N} G_{ik}(\, {V_{c,n}}^2 + {V_{c,m}}^2 - 2\, V_{c,n}\, V_{c,m} \cos\theta_{c,nm}) \tag{12}$$

$$Losses = \sum\{Losses_a + Losses_b + Losses_c\} \tag{13}$$

where $V_{a,b,c,n}$and $V_{a,b,c,m}$ are the voltages across the lines per phase, in other words, they are the buses voltages and the phase angle between them presented by $\theta_{nm,a,b,c}$ for each phase. Transmission losses are very important in our case since the target is to reduce these losses as much as possible to increase efficiency of the proposed system, the losses are expected to be changed based on time also.

The voltage boundaries are one of the challenges which face the high level of penetration of renewable energy sources in the grid. Since connecting these sources to busses may cause an increase in the voltage to undesirable values, which may affect users. A storage system is helpful in solving this issue by charging/discharging to achieve the targeted value. Equation (14) shows the voltage boundaries for the target voltage:

$$\mathrm{V}_{min} < \mathrm{V}_{bus}(\mathrm{i}) < \mathrm{V}_{max}, \text{where } \mathrm{i} \in (1, \mathrm{N}) \quad (14)$$

where V_{min} and V_{max} will be defined as (-10% to +10%) of the rated voltage [52]. Each phase on the system shall meet this criterion to achieve the maximum reliability from the system. On the other hand, the voltage balance will be achieved if the controller keeps these voltages in the acceptable range. This is based on the IEEE definition "Voltage unbalance, known as the Phase Voltage Unbalance Rate (PVUR)", and is expressed by equations (15) - (20):

$$\%PVUR = \frac{max\ voltage\ deviation\ from\ the\ avg\ phase\ voltage}{avg\ phase\ voltage} = \frac{V_{divmax}\,(t,i)}{|V_{avg}\,(t,i)|} \quad (15)$$

$$V_{avg}\,(t,i) = [|V_a(t,i)| + |V_b(t,i)| + |V_c(t,i)|]/3 \quad (16)$$

$$V_{deva}\,(t,i) = abs[|V_a(t,i)| - |V_{avg}\,(t,i)|] \quad (17)$$

$$V_{devb}(t,i) = abs[|V_b(t,i)| - |V_{avg}(t,i)|] \quad (18)$$

$$V_{devc}(t,i) = abs[|V_b(t,i)| - |V_{avg}(t,i)|] \quad (19)$$

$$V_{devmax}(t,i) = \max[\,|V_{diva}(t,i)|, |V_{divb}(t,i)|, |V_{divc}(t,i)|] \quad (20)$$

It is a similar definition to NEMA, but the difference is that IEEE uses phase voltage whilst NEMA uses line voltage [51].

Storage system that will be used in this thesis is the battery system. Stored energy in the battery could be identified by the State of Charge (SOC). The percentage of the SOC will decide the operation mode of the charger/inverter of the system; either to charge or discharge. Equation (21) illustrates that. The efficiency of charge mode differs from discharge mode [33];

$$E(t,i) - E(t-1,\mathrm{i}) = \eta c\ Pc\ (t,i) - \frac{1}{\eta d}\ Pd(t,i);\ where\ i\ \epsilon\ (1,N) \quad (21)$$

where,

E (t,i)	Energy level for battery of EV for agent i in period t
η_c	Efficiency of charging
η_d	Efficiency of discharging
P_c	Charge energy for electric vehicle for agent i at period t
P_d	Discharge energy for electric vehicle for agent i at period t

Since the EV could be connected to single phase or three phase sources, the algorithm will deal with the charge/discharge on the three phase to optimally find a solution of charging/discharging for appropriate phase, equation (22) & (23) represent that, the charge/discharge will be from any phase knowing that (+) sign means (or) which allow the algorithm to charge or discharge from any phase:

$$P_{Charge}(t,i) = P_{charge,a}(t,i) + P_{charge,b}(t,i) + P_{charge,c}(t,i) \qquad (22)$$

$$P_{Discharge}(t,i) = P_{discharge,a}(t,i) + P_{discharge,b}(t,i) + P_{discharge,c}(t,i) \qquad (23)$$

The agents most of the time need their battery to be fully charged, the proposed study here assumes that the agents want their cars fully charged at 24:00, The stored energy in each storage system is formulated by equation (24).

$$E\ (24,i) = 20\ kWh\ , where\ i\ \epsilon\ (1,N) \qquad (24)$$

where,

E	Stored Energy in the battery
N	Number of Buses

After collecting all these information, the optimization equations, which can be used to get an optimal solution for all energy cases, and to maintain the grid within standard regulations and minimal cost will be used. Equation 25, illustrates the optimization equation.

$$\min\{\sum_{i=1}^{N} P_{gen} + \text{Losses} - P_{pv}\} \quad (25)$$

Regarding the definition of the penetration level of the RES with the existing grid is defined as equation (26), where the high penetration considered as higher than 50 % and low penetration for less than 50% [53],

$$Penetration = \frac{P_{PV\,rated\,peak}}{P_{Load\,rated\,peak}} \quad (26)$$

Below are all the boundary conditions that will be used in this thesis, and programed with GAMS code:

$0.9 < V_{a,b,c} < 1.1$, $where\ V\ is\ in\ per\ unit$

$-10000 < P_{gen,a,b,c} < 10000$, $where\ P\ is\ in\ per\ unit$

$-10000 < Q_{gen,a,b,c} < 10000$, $where\ Q\ is\ in\ per\ unit$

$pf_{pv} = 0.95$

$PVUR = 0.05\ \%$

$P_{discharge,charge} = 10\ kW$

$SOC_0 = 8\ kWh$

$6\ kWh < SOC(t,i) < 40\ kWh$

4.3 Algorithm Flow Chart

The algorithm flow chart for the optimizer is shown in Figure (4.2), the controller will check all the boundaries defined conditions such as PVUR, SOC and voltage values for the three phase, if all the values are not within the boundaries, it will discharge the EV to get all the values within the ranges, otherwise the controller will go to the second step of optimization which aim to minimize line losses and total energy of the busses, the controller will charge EV at (t=24) to 100% of SOC, if not it will recharge EV and check all the parameter again, by the end of the cycle it will show the calculated PVUR, Line Losses and total energy of the system. The output signal of this controller will end a gate signal to connected inverter to charge/discharge storage system on the busses as shown in figure (4.1). Noting that, the assumption of implementing this solution to control the charge/discharge from/to any phase of the system, that there is a selector on the inverter to select the targeted phase or three phases.

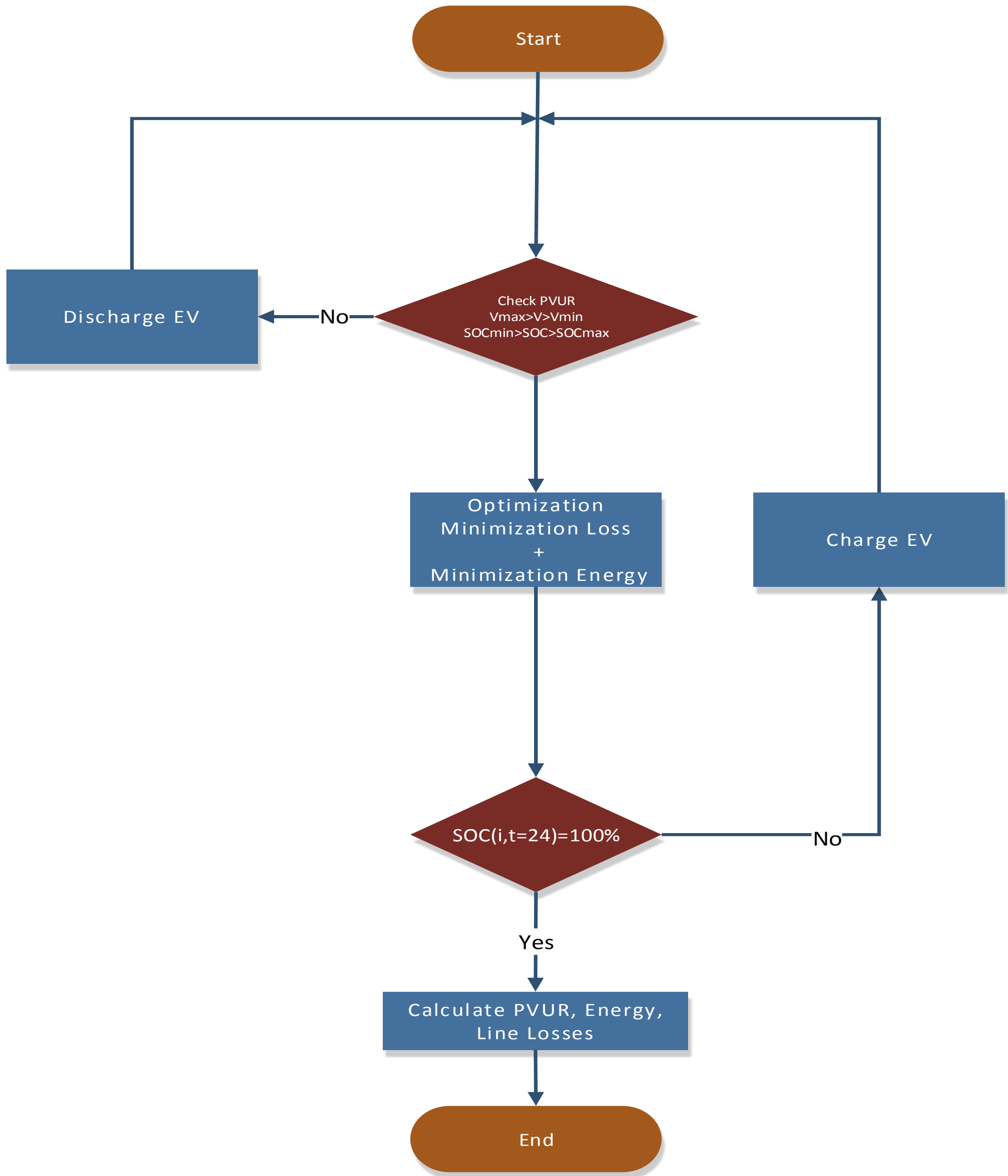


Figure 4. 2:: Algorithm Flowchart

Chapter 5 Simulation and Result

A simulation was conducted for the circuit with the following scenarios:

I. Unbalanced load with high penetration levels from PV and storage systems.
   a. Charging/Discharging all the time is allowed by the optimizer
   b. Charging/Discharging is allowed from 16:00-20:00
II. Unbalanced load with high penetration levels from PV and high penetration of storage systems.
   a. Charging/Discharging all the time is allowed by the optimizer
   b. Charging/Discharging is allowed from 16:00-20:00
III. Unbalanced load with low penetration levels from PV and storage systems.
   a. Charging/Discharging all the time is allowed by the optimizer
   b. Charging/Discharging is allowed from 16:00-20:00
IV. Unbalanced Loads with PV system and storage system with doubling the load on phase two, and the algorithm will not allow the controller to charge/discharge on the other phases
V. Unbalanced three phase with high penetration levels from PV and high penetration of storage systems.

Case I High penetrations of RES and Storage System:

The case scenario is radial system, the line long is 100 m, with high penetration on PV and storage system as in Figure (5.1). The load profile used in this configuration is Birzeit housing in Al-Tira, which is unbalanced as illustrated in Figure (5.2). The algorithm will find the optimal solution to supply the load power, while keeping the losses on the system as low as possible, maximizing the output PV power, and keeping the voltage balanced on the three phases.

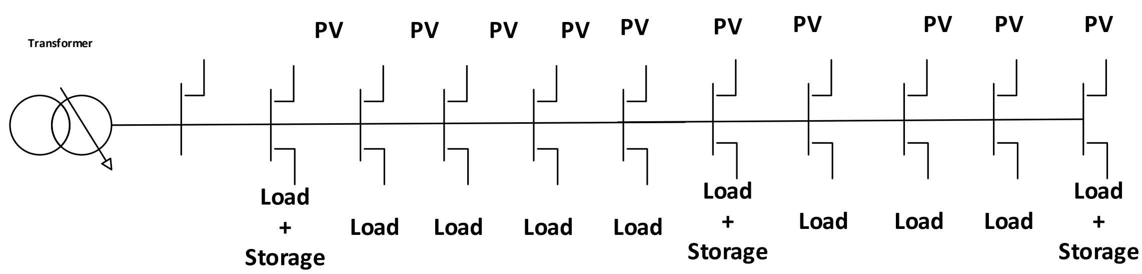


Figure 5 1: The Circuit Diagram of Case I

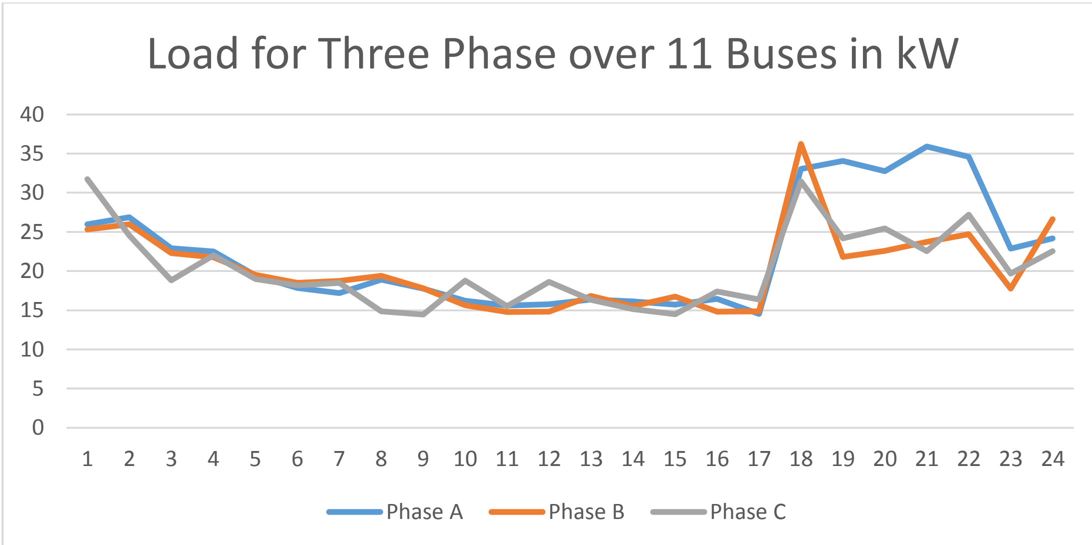


Figure 5 2 : Average load per phase over all the buses

OpenDSS was used to simulate this circuit to get the phase voltage and line losses. The results show that, the voltages over the three buses are not balanced as shown in Figure (5.3). It is obvious that, the voltages are unbalanced between the three phases, and the PVUR is less than 5%, but the voltage breaches the allowed boundaries of voltage, which is -10%. The optimizer (GAMS) solved this circuit to achieve all the boundaries. The three phase voltages results are shown in Figure (5.3). The voltage at 14:00, in normal case, reaches 231 V, while in optimization it didn't reach that due to charging the storage system. At 16:00, the load reaches its maximum value, so as expected the voltage will be decreased in both cases. The behavior of the three phase almost same as trending, but the limitation condition for the voltage balance and objective function keep three phase voltage higher than the normal case. Regarding the power, the load power was supplied by the utility and stored energy during the low irradiance level. But during PV generation, most of the load power is supplied from the PV system. Between 10:00 -17:00, in the optimization case the generated energy was higher than the normal case, since PV generation was used to charge the storage system, but with the normal case the PV generated power during the same period was less since storage system wasn't charged at same time. By using the optimizer, the generation may be smaller than normal case, but voltage balance and minimum loss make this difference, as illustrated in Figure (5.4). This is one of benefits of using optimization with renewable energy sources. Figure (5.5) presents the start time for the charging the storage system.

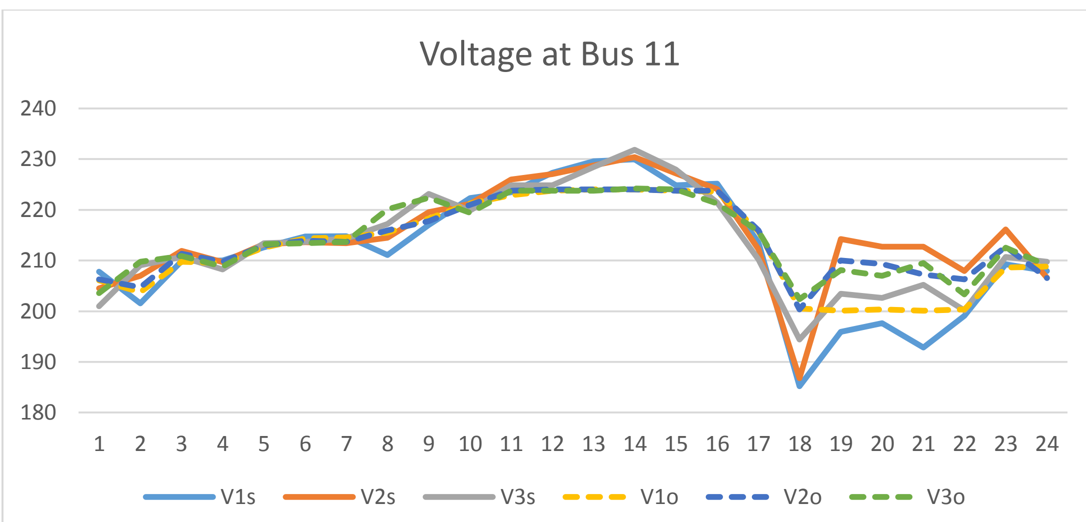


Figure 5 3 : Three Phase Voltages at Bus 11 with using the optimizer (V1o, V2o and V3o) and without using the optimizer (V1s, V2s and V3s Case I configuration)

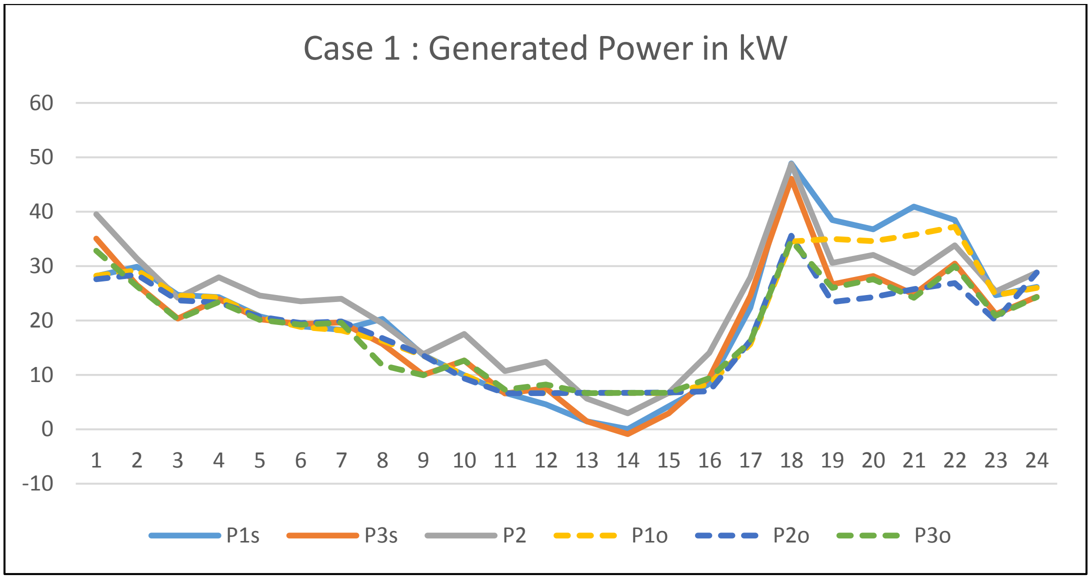


Figure 5 4 : The Generated Power from Utility with using the optimizer (P1o, P2o and P3o) and without using the optimizer (P1s, P2s and P3s) for Case I configuration

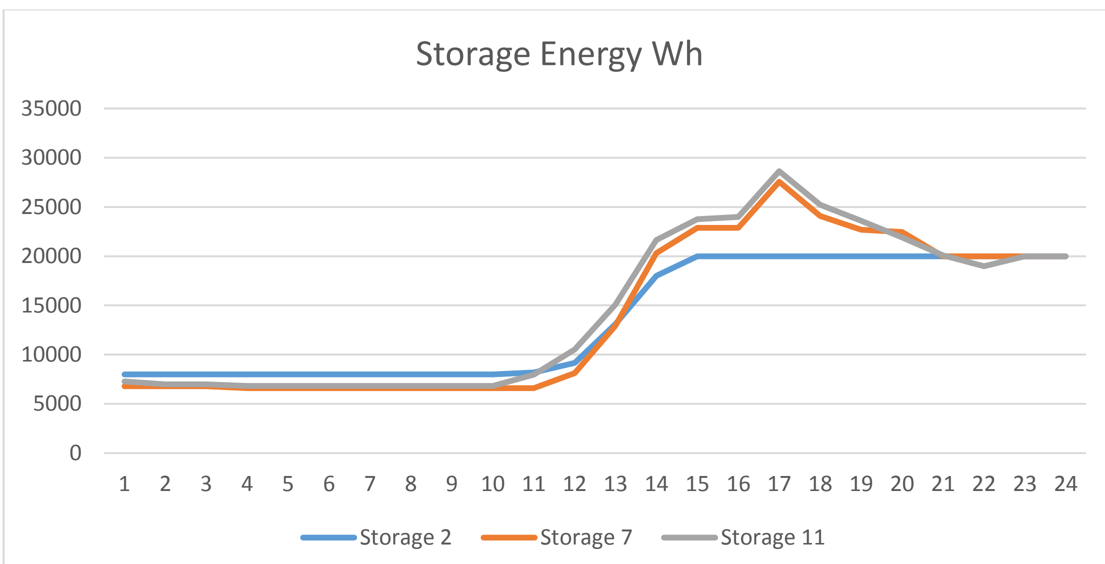


Figure 5 5 : Storage Energy for Case I charge and discharge allowed at any time

For the same circuit but the charge and discharge for the EV period is limited from 16:00 to 20:00, which is the time that most of users try to connect their cars to the grid. After simulating the circuit using OpenDss and applying the optimizer algorithm, the optimizer kept three phase voltages on the last bus between (194-231) V during high PV generation, and its behavior is the same as the normal case, which means that the optimizer utilizes PV generations to supply the load power, but when the optimizer starts charging the storage system, the three phase voltages become 220 V, since the demand increases for the period between 16:00-18:00, while it reaches 200 V without using the optimization algorithm, as shown in Figure (5.6). On the other hand, the generated power from the PV system cannot cover the load and the storage at the same time.

This is the explanation of the generated power behavior in Figure (5.7) between 16:00-17:00, since the PV generation still available due to sunshine in this period. The algorithm also achieves the target in keeping the storage energy of 20 kWh at 24 H, as shown in Figure (5.8). Regarding the PVUR over 24 hours, Figure (5.9) shows the PVUR difference between the three cases.

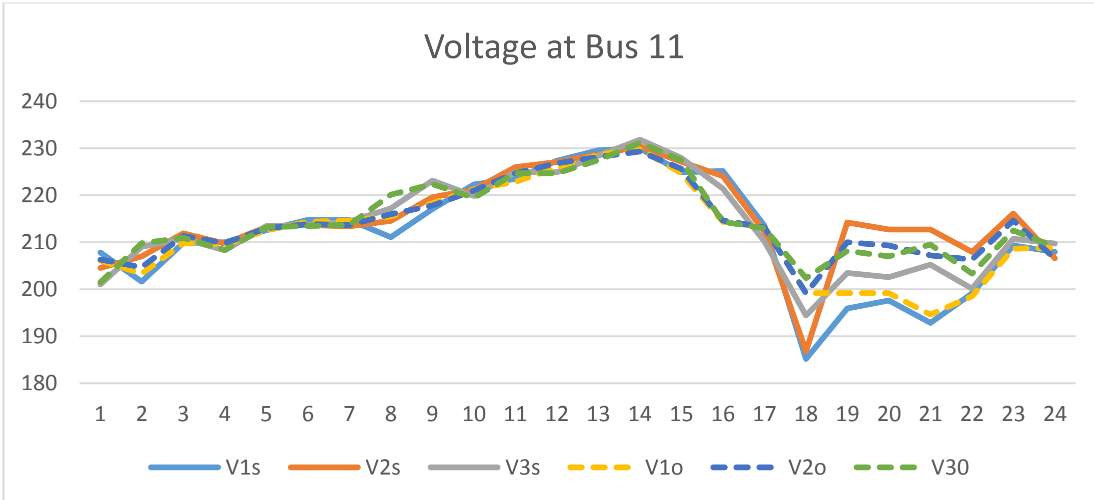


Figure 5 6 : Three Phase Voltages at Bus 11 with using the optimizer (V1o, V2o and V3o) and without using the optimizer (V1s, V2s and V3s Case I configuration with limited time of charging and discharging

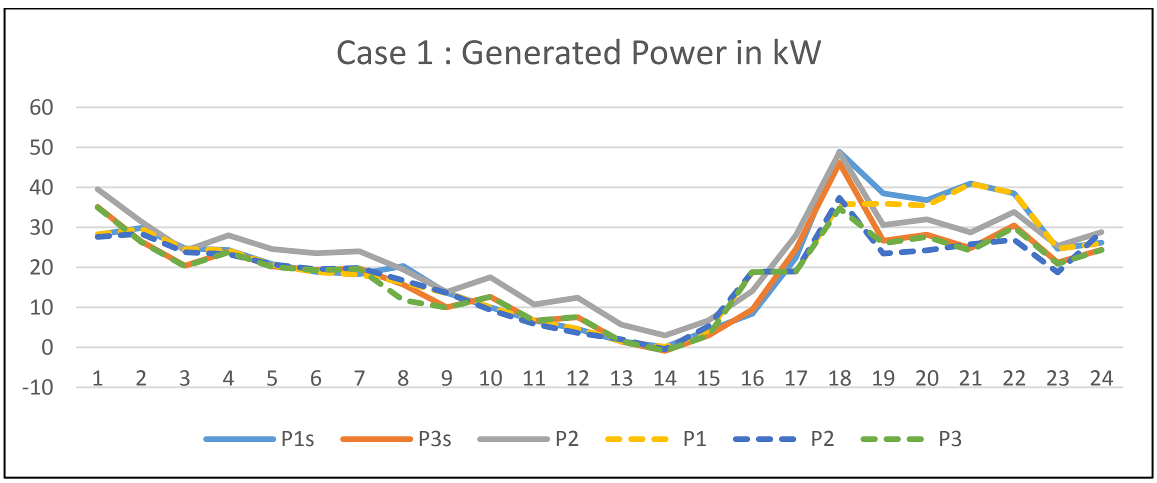


Figure 5 7 : The Generated Power from Utility with using the optimizer (P1o, P2o and P3o) and without using the optimizer (P1s, P2s and P3s) for Case I configuration with limited time of charging and discharging

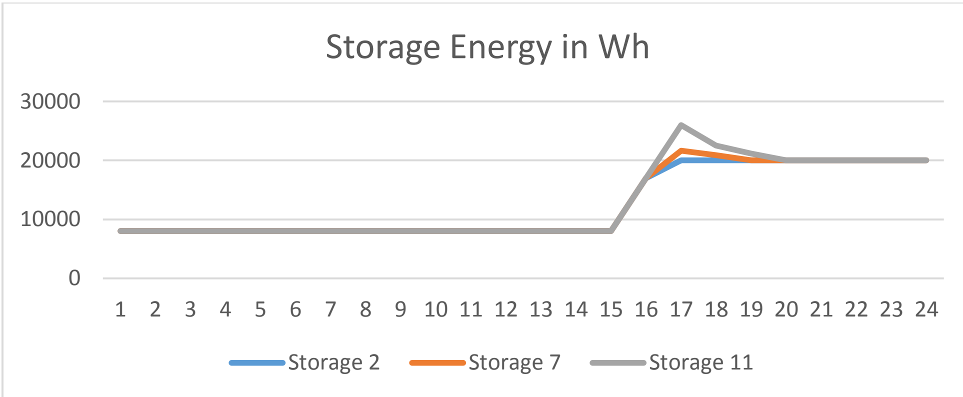


Figure 5 8 : : Storage Energy for case I charge and discharge allowed from 16:00-20:00

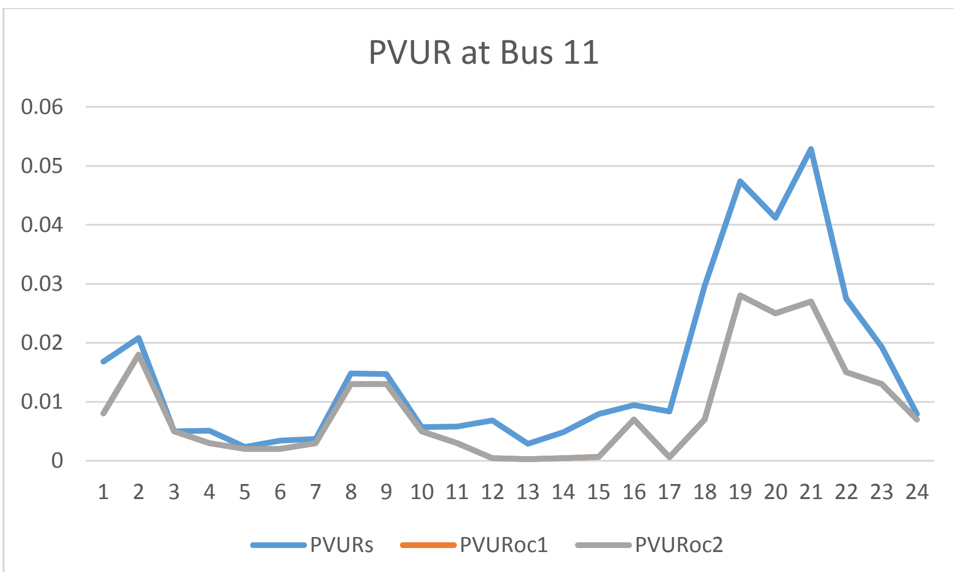


Figure 5 9 : PVUR for case I , where PVURs is the simulated without optimizer and PVURoc1 is with optimizer for 24 hours simulation and PVURoc2 is the limited simulation time

Case II High Penetration of RES and High Penetration of Storage System:

In this case, the PV penetration will be decreased to be only on 4 busses 2, 4, 6 and 9, and the storage system will be the same as before. The penetration of PV in this system is around 50% of the load. Figure (5.10) illustrates the circuit diagram for this case.

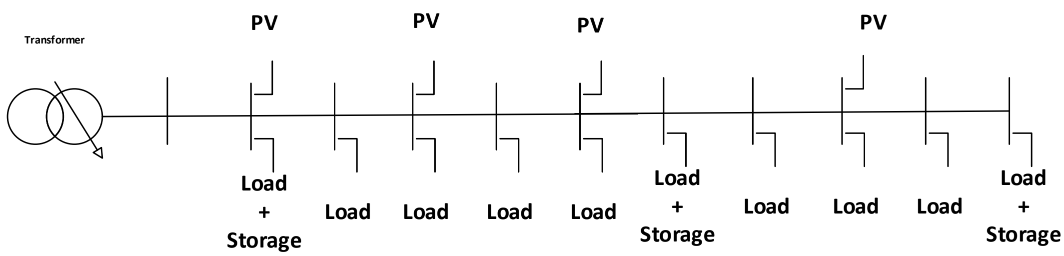


Figure 5 10 : Circuit Diagram for Case II

The simulation of this circuit using OpenDSS shows that the voltages are always between (185-222) V. The lowest value occurs at the start of charging EV during the period 18:00-19:00, and the voltage increased after that, as charging is finished. The highest value occurs during the PV generation especially at 14:00. While by using the optimization algorithm the voltages always alternate between (198-217) V, as can be seen in Figure (5.11). The highest value was during the PV generation and the lowest value was during the peak load; between 18:00-22:00. Regarding the power, the optimizer, as in Case I, utilizes PV generation to charge EV and this explains why the utility voltages using the optimizer are higher than those obtained by non-optimized solution as Figure (5.12) and Figure (5.13) displays the start time of charging the EV.

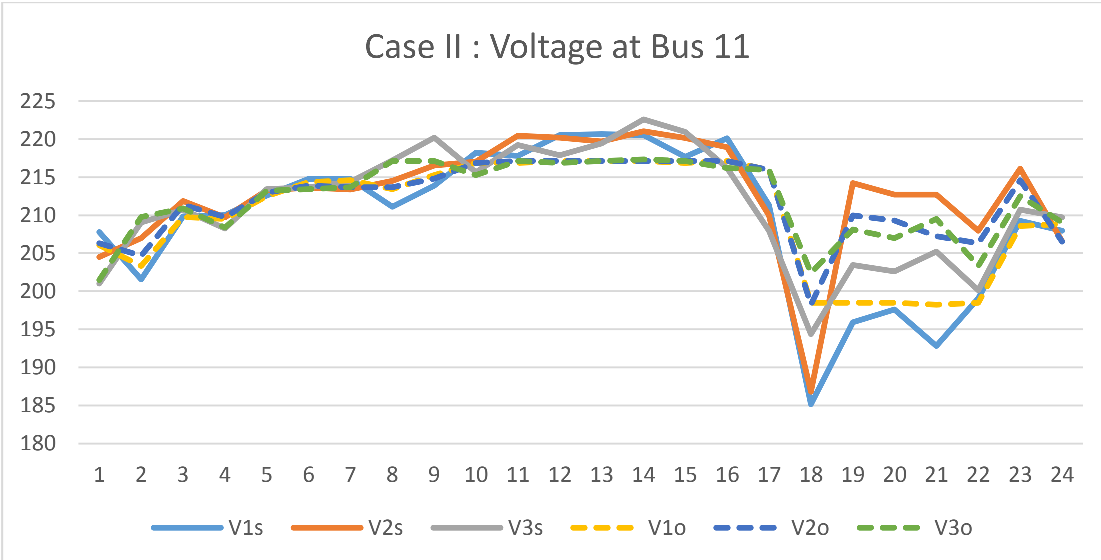


Figure 5 11 : Three Phase Voltages at Bus 11 with using the optimizer (V1o, V2o and V3o) and without using the optimizer (V1s, V2s and V3s Case II configuration

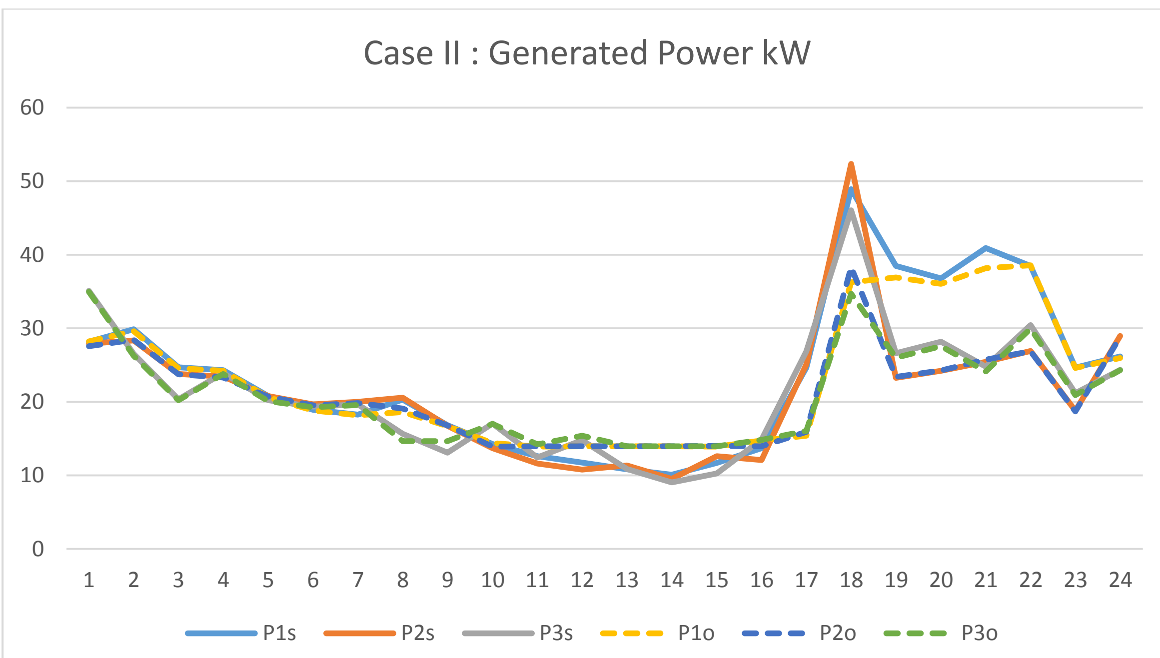


Figure 5 12 : The Generated Power from Utility with using the optimizer (P1o, P2o and P3o) and without using the optimizer (P1s, P2s and P3s) for Case II configuration

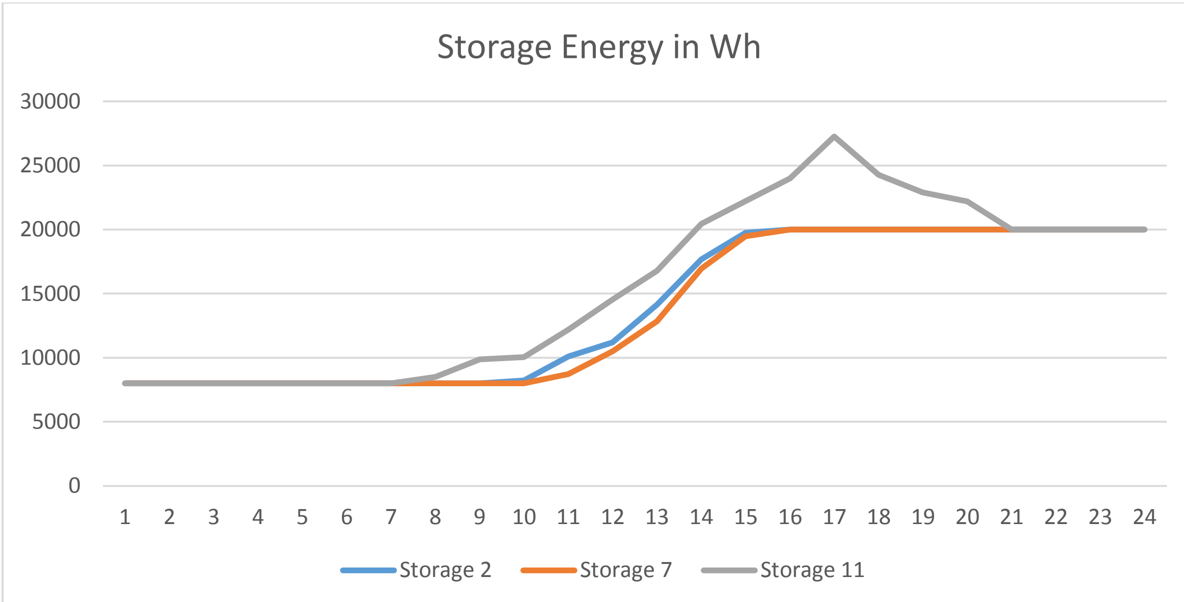


Figure 5 13 : Storage Energy for case II charge and discharge allowed any time

Similar to the first case, the charge and discharge period is limited between 16:00-20:00. In Figure (5.14), the three phase voltages obtained by non-optimized case are still between (185-222) V and the highest value occurs at the PV generation peak, whilst the lowest value occurs when the system starts charging EV. After applying the optimizer, the three phase voltages become higher and fall between (194-221) V. The largest value occurs, as the non-optimized case, when the PV generation reaches its peak value, while the lowest level occurs when the controller starts charging the EV. The power obtained from the utility decreases when PV starts generating power for both non-optimized and optimized case. But, when the controller starts charging the EV implementing the optimizer, it utilizes PV generated power to cover this energy, as illustrated in Figure (5.15) and reflected in voltage profile. Energy stored in the EV reaches the target energy, which is 20 kWh after two hours, as shown in Figure (5.16). Regarding the PVUR for the three simulation cases shown in Figure (5.17).

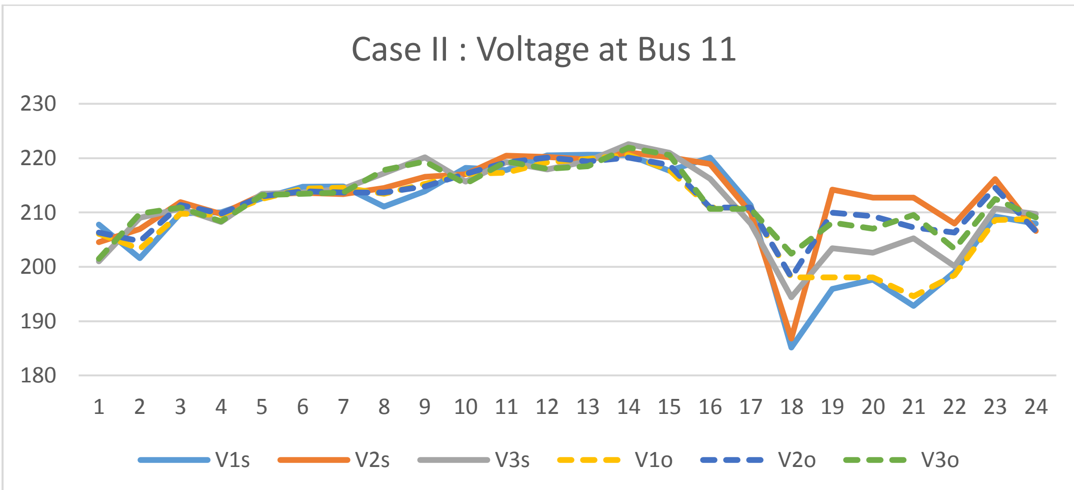


Figure 5 14 : Three Phase Voltages at Bus 11 with (V1, V2 and V3) and without (V1s, V2s and V3s) using the optimizer for Case II configuration with limited time of charging and discharging

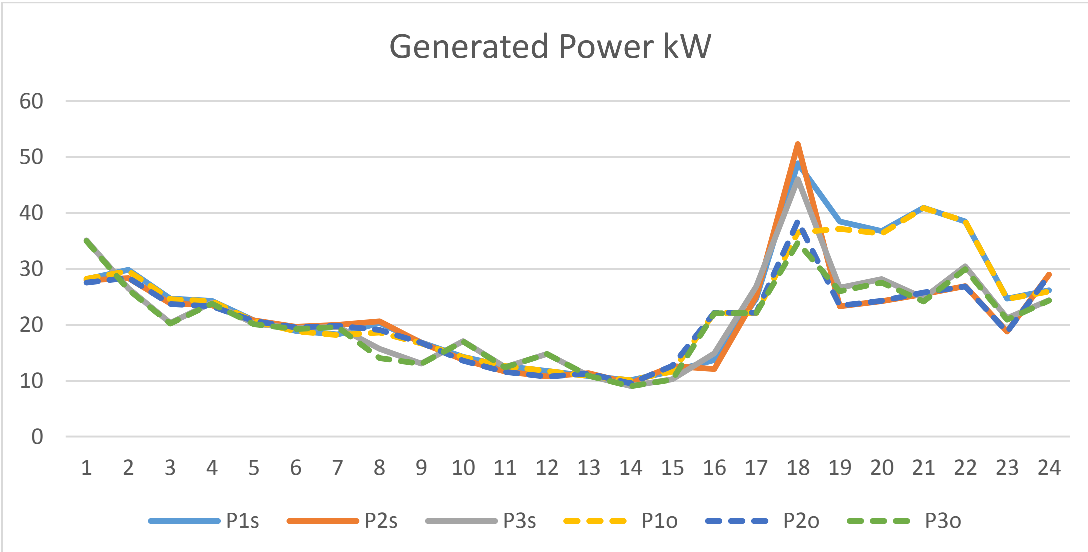


Figure 5 15 : The Generated Power from Utility with using the optimizer (P1o, P2o and P3o) and without using the optimizer (P1s, P2s and P3s) for Case II configuration with limited time of charging and discharging

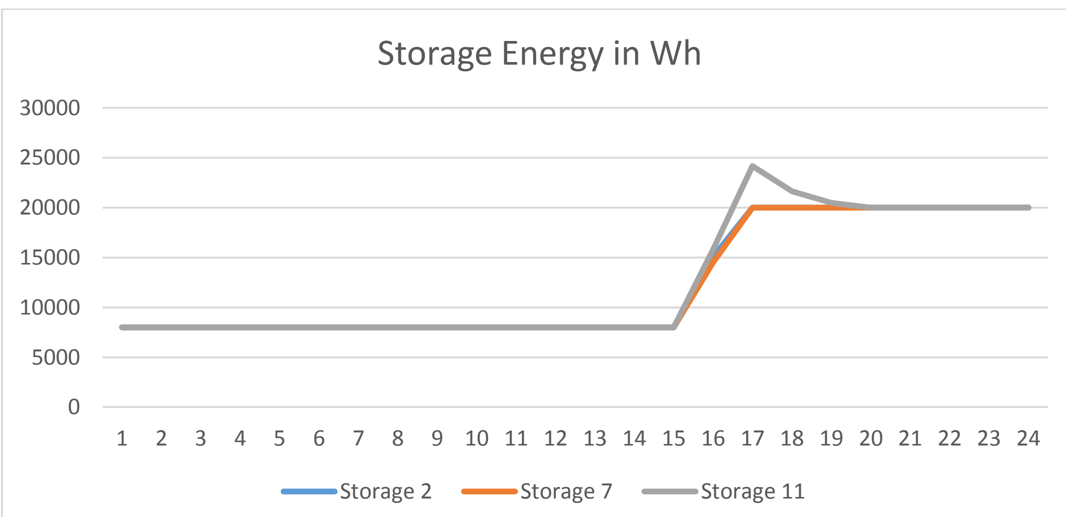


Figure 5 16 : Storage Energy for case II charge and discharge allowed from 16:00-20:00

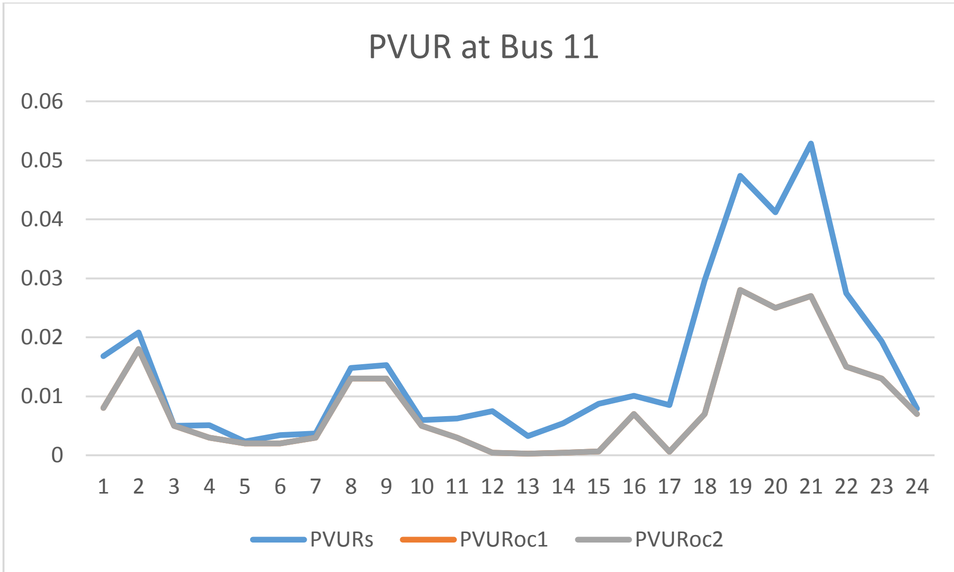


Figure 5 17 : PVUR for case II , where PVURs is the simulated without optimizer and PVURoc1 is with optimizer for 24 hours simulation and PVURoc2 is the limited simulation time

Case III Low Penetrations of RES and Storage System:

In this case, the penetration of PV is 10% of the load and storage system will be only on bus 7, where the PV installed in first bus randomly, as shown in Figure (5.18).

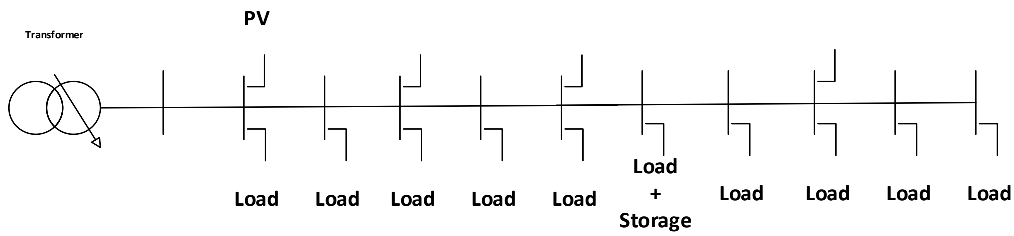


Figure 5 18 : Circuit Diagram for Case III

The simulation results shown in Figure (5.19), shows that, the three phase voltages at the last bus are between (190-218) V, where the highest value occurs at the PV peak generation and the lowest value occurs after the start of charging EV at 18:00. On the other hand, after applying the optimizer, which will try to achieve minimum power loss and keep the voltages within an acceptable range. The result shows that, the three phase voltages are between (197-216) V, where the highest value occurs at the PV peak generation, and the voltage remain constant during this period 10:00-17:00, while it fluctuations in the non-optimized case. The generated power in Figure (5.20) shows that, the PV generation helps the utility to cover the load during the generation period for both cases. It seems that, there is no difference between the generated power for non-optimized and optimized case, but the voltage balance is achieved and the losses are decreased after applying the optimizer algorithm, knowing that the penetration of EV is around 10%. The controller starts charging EV just after the sunrise hour, which indicates that the optimizer utilizes RES to cover charging EV, as shown in Figure (5.21).

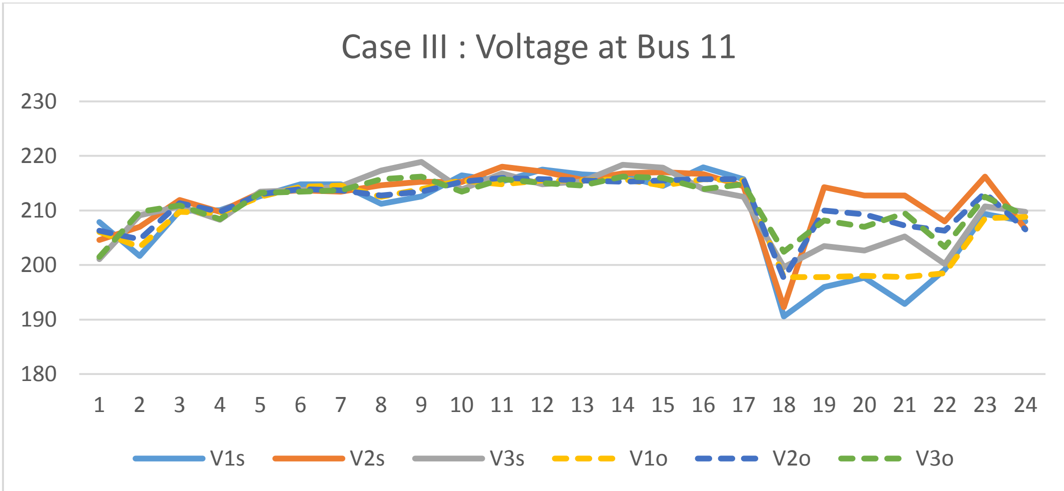


Figure 5 19 : Three Phase Voltages at Bus 11 with using the optimizer (V1o, V2o and V3o) and without using the optimizer (V1s, V2s and V3s Case III configuration

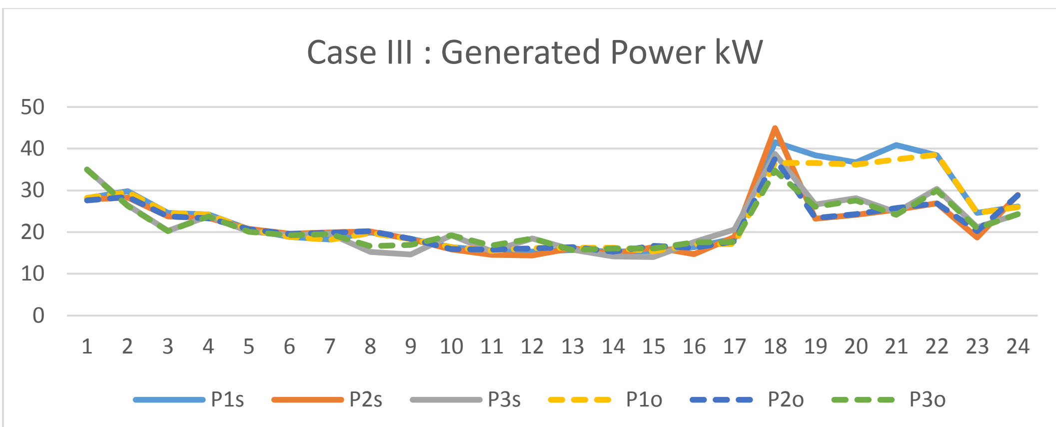


Figure 5 20 : The Generated Power from Utility with using the optimizer (P1o, P2o and P3o) and without using the optimizer (P1s, P2s and P3s) for Case II configuration

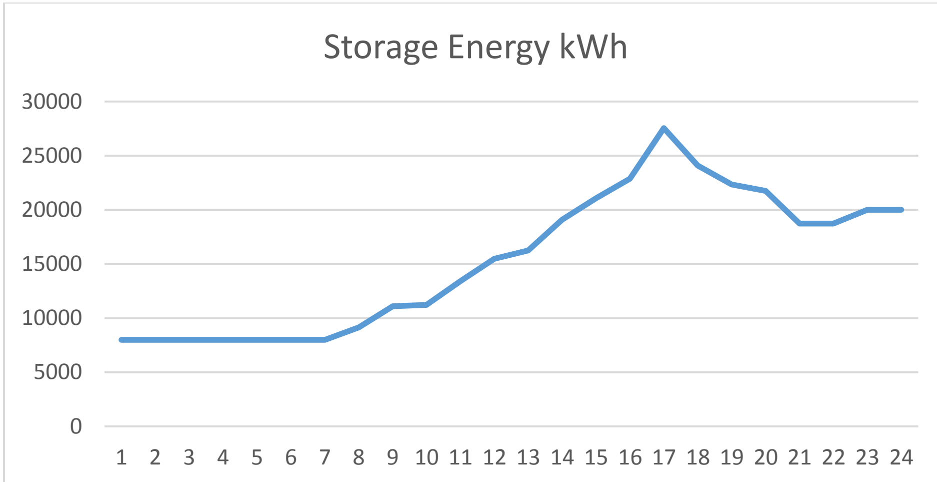


Figure 5 21 : Storage Energy for case III charge and discharge allowed any time

Same as mentioned for the previous cases, applying the limited charging and discharging period between 16:00-20:00 on the EV, the three phase voltages for the normal and the optimized case are displayed in Figure (5.22), which are between (194-218) V in optimized case where the highest value at PV generation period and the lowest value after charging EV, while (190-218) V in non-optimized case, the generated power almost equals between the two cases this is due to penetrations of EV and PV, as shown in Figure (5.23). The controller starts to charge the EV in 16:00 and finished after two hours, the first hour from the PV generation and the second from utility as shown in Figure (5.24). Regarding the PVUR for the three simulation cases shown in Figure (5.25).

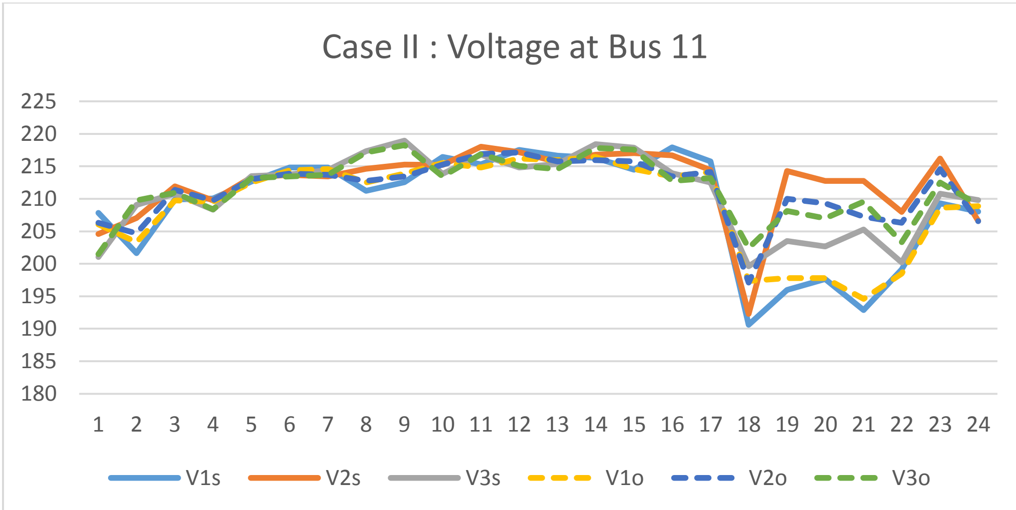


Figure 5 22 : Three Phase Voltages at Bus 11 with (V1, V2 and V3) and without (V1s, V2s and V3s) using the optimizer for Case III configuration with limited time of charging and discharging

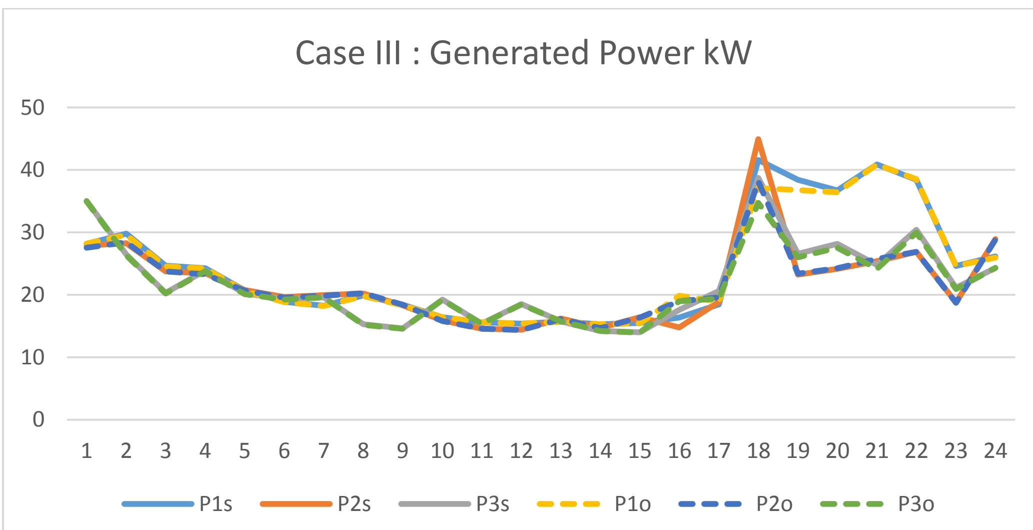


Figure 5 23 : The Generated Power from Utility with using the optimizer (P1o, P2o and P3o) and without using the optimizer (P1s, P2s andP3s) for Case III configuration with limited time of charging and discharging

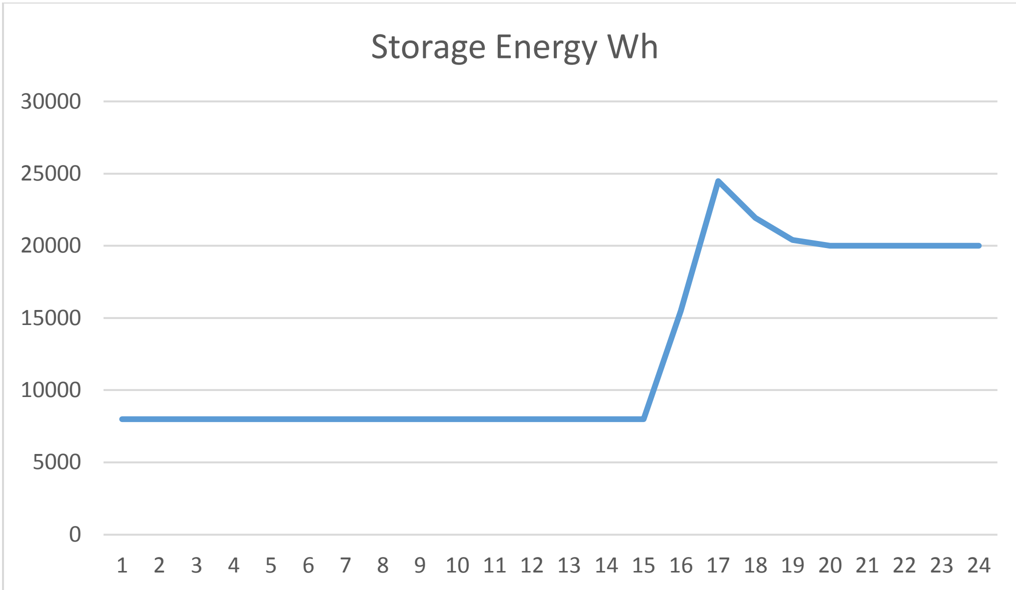


Figure 5 24 : Storage Energy for case III charge and discharge allowed from 16:00-20:00

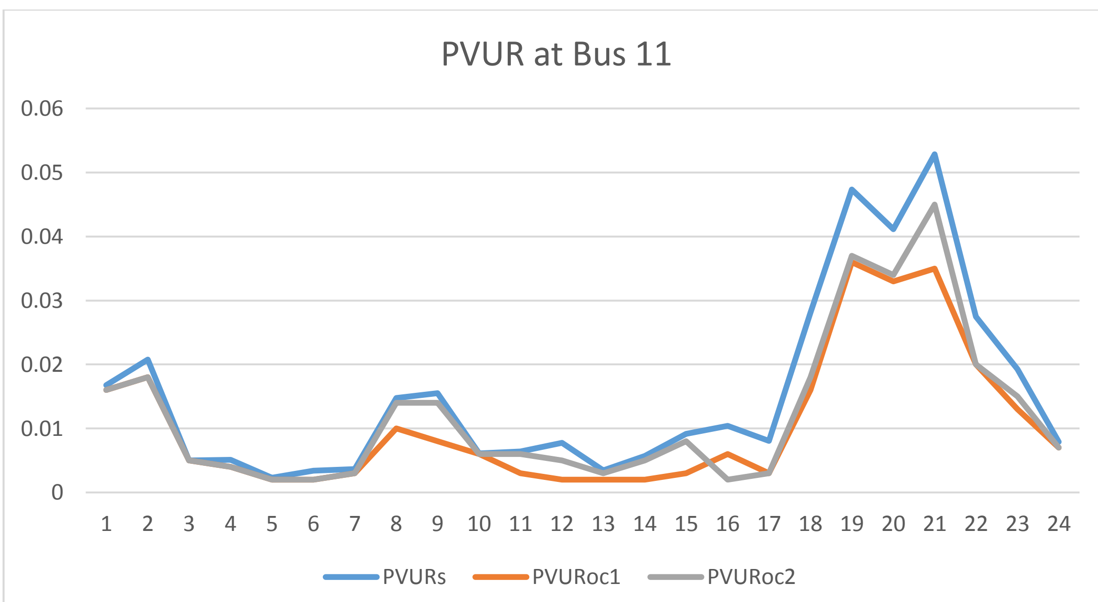


Figure 5 25 : PVUR for case III , where PVURs is the simulated without optimizer and PVURoc1 is with optimizer for 24 hours simulation and PVURoc2 is the limited simulation time

Case IV Unbalanced Phases and Charge/Discharge from this Phase B only:

In this case, the PV penetration about 10% and all the storage systems are connected to bus 7 only. The controller will allow the charge and discharge on phase two only, while the load on same phase is increased by 150%. This case will show how the optimizer will deal with this extreme case, as in Figure (5.26), the three phase voltages at the last bus are enhanced after using the algorithm especially for phase 2, where the lowest value is 186 V in optimized and 167 V in non-optimized case; the optimizer increased the voltage level around 20 V.

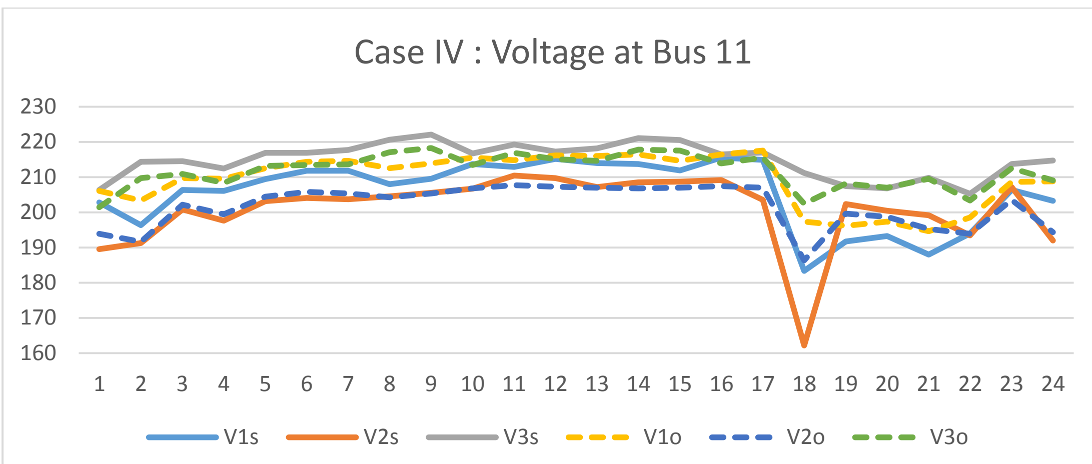


Figure 5 26 : Three Phase Voltages at Bus 11 with (V1, V2 and V3) and without (V1s, V2s and V3s) using the optimizer for Case IV configuration

On the other hand, the generated power using optimizer is higher to cover the load and charge EV from one side and keep the voltage balance from the other side, as shown in Figure (5.27). One of the controller targets is to charge EV to 20 kWh, the controller succeeds in this and it starts charging from 10:00 till 16:00, as clearly seen in Figure (5.28). Regarding the PVUR for the two simulation cases shown in Figure (5.29).

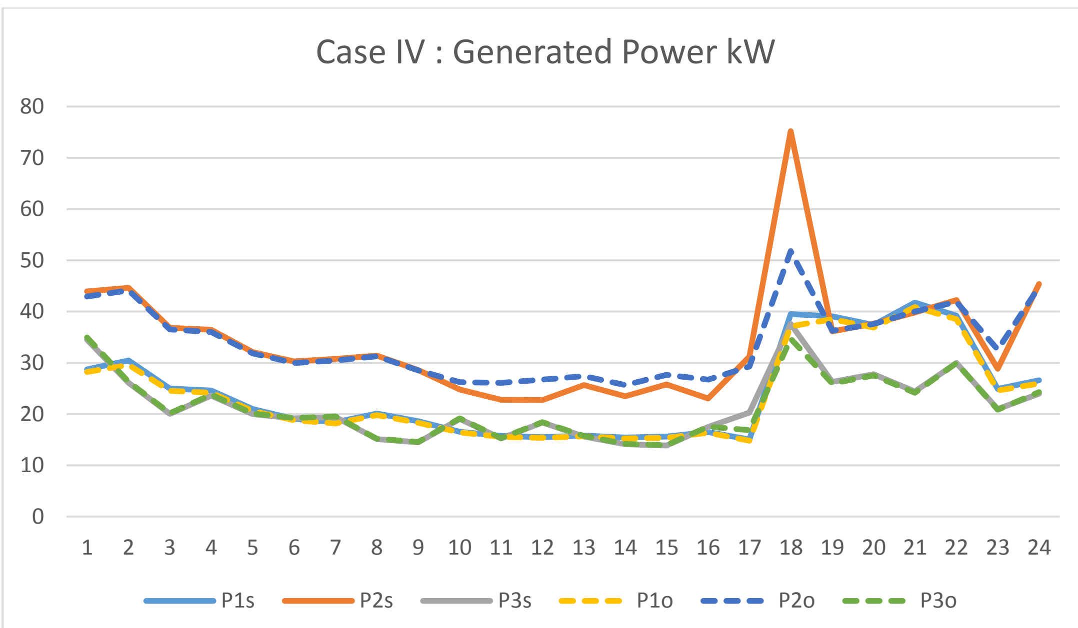


Figure 5 27 : The Generated Power from Utility with using the optimizer (P1o, P2o and P3o) and without using the optimizer (P1s, P2s andP3s) for Case III configuration

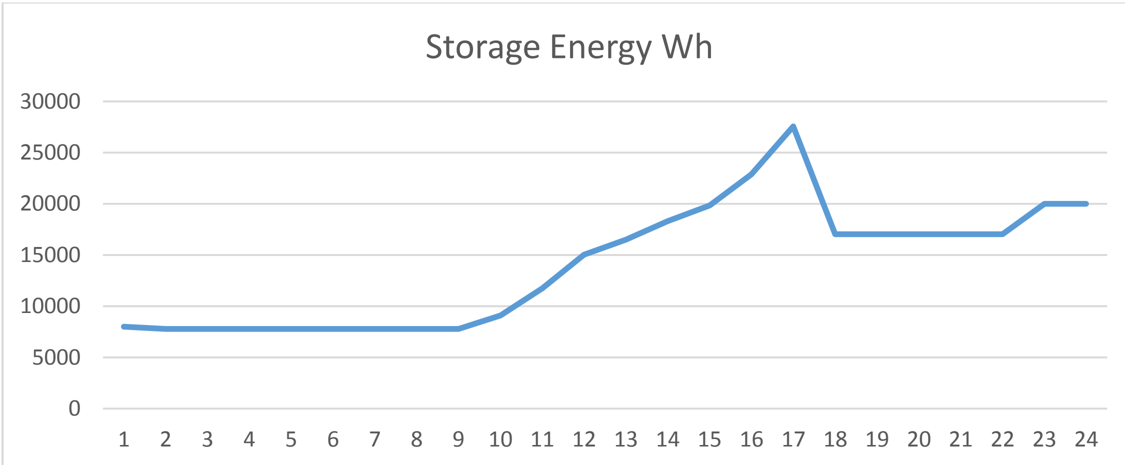


Figure 5 28 : Storage Energy for case IV charge and discharge allowed any time

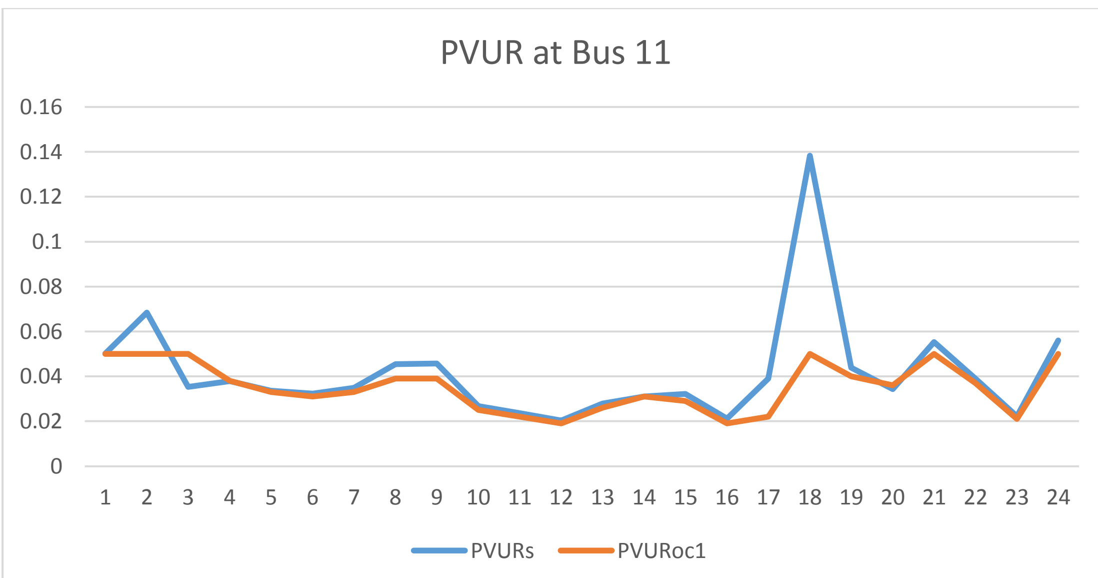


Figure 5 29 : PVUR for case IV , where PVURs is the simulated without optimizer and PVURoc1 is with optimizer

Case V Three Unbalanced Phases with High Penetration Level from RES and EV:

In this case the optimization will deal with unbalanced three phase load, the first bus is loaded as before cases, the second phase is loaded as 125% and the third phase is 50%. The result will show that the voltage across the third phase is higher than the others since the load is lower and the voltage across the second on is the lowest as illustrated in Figure (5.30). Regarding the generated power, the non-optimized solution showed that the generation is reversed on phase three since the load is low but by using the optimizer the power didn't reversed and the optimizer using this energy to charge the EV as shown in Figures (5.31) and (5.32). Regarding the PVUR for the three simulation cases shown in Figure (5.33).

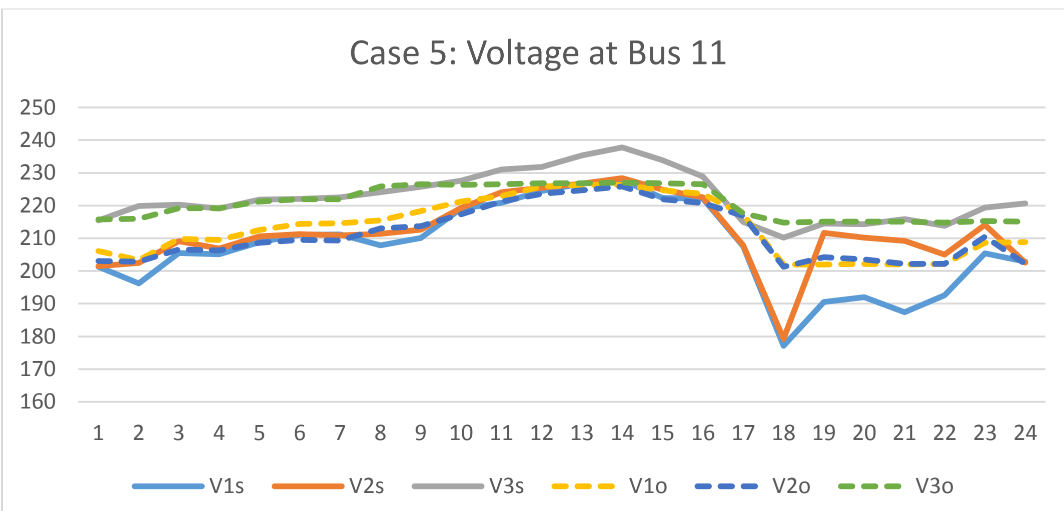


Figure 5 30: Three Phase Voltages at Bus 11 with (V1, V2 and V3) and without (V1s, V2s and V3s) using the optimizer for Case V configuration

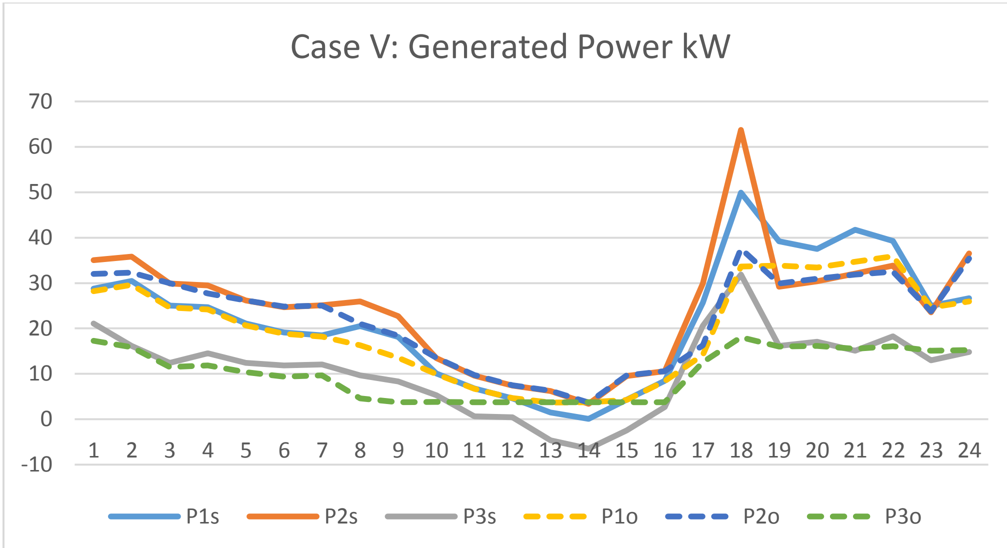


Figure 5 31 : The Generated Power from Utility with using the optimizer (P1o, P2o and P3o) and without using the optimizer (P1s, P2s andP3s) for Case V configuration

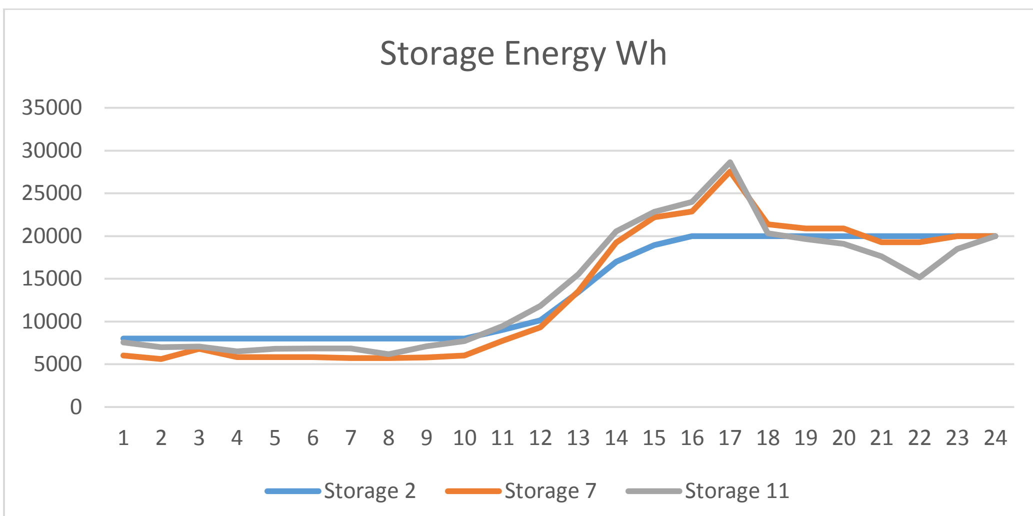


Figure 5 32: Storage Energy for case V charge and discharge allowed any time

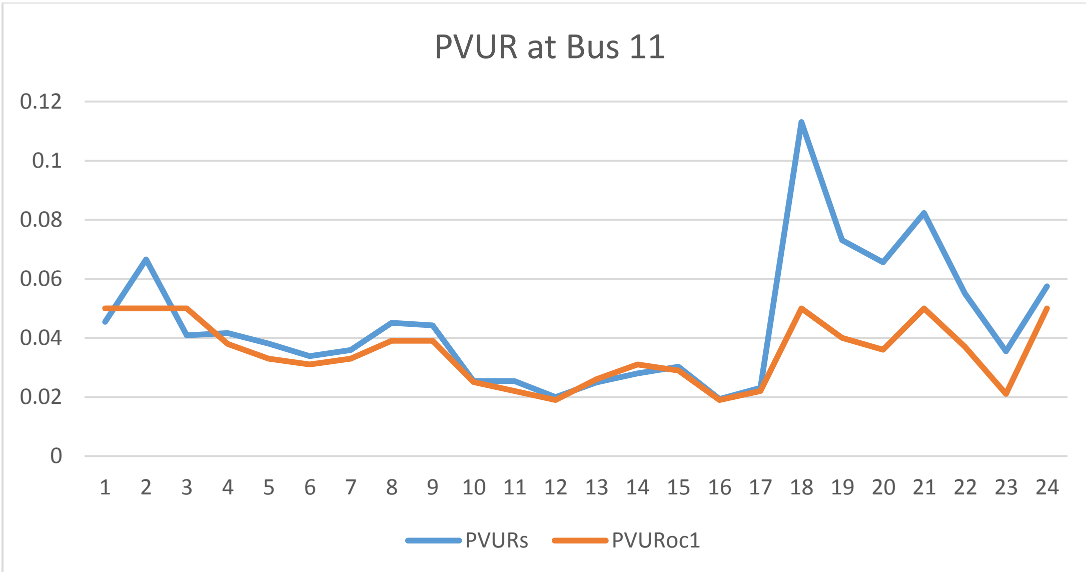


Figure 5 33 : PVUR for case V , where PVURS is the simulated without optimizer and PVURoc1 is with optimizer

As a summary for all above results, table I shows the difference between the optimized and non-optimized solution:

Table I : Summary Results of all Cases

Case	**Simulation Tool**	**Period of Simulation**	V_{min}	V_{max}	V_{devmax}	***Losses kWh***	$PVUR_{max}$	***Energy kWh***
Case I	*OpenDSS*	*00:00-24:00*	185	231	10.76	110	0.046	1421
	Optimizer	*00:00-24:00*	200	224	5.98	94	0.026	1370
	Optimizer	*16:00-20:00*	194	231	9.2	98	0.04	1379

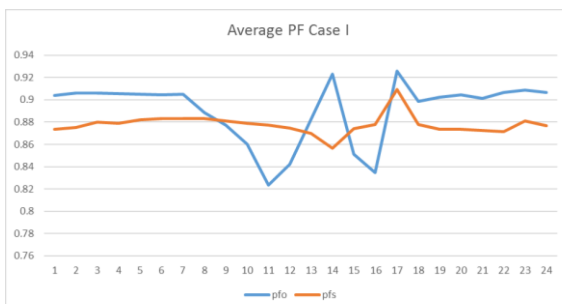
Case II	*OpenDSS*	*00:00-24:00*	185	222	10.7	120	0.048	1587
	Optimizer	*00:00-24:00*	198	217	7.05	106	0.032	1549
	Optimizer	*16:00-20:00*	194	221	9.2	109	0.041	1550
Case III	*OpenDSS*	*00:00-24:00*	190	218	10.7	120	0.05	1622
	Optimizer	*00:00-24:00*	197	216	7.51	113	0.035	1600
	Optimizer	*16:00-20:00*	194	218	9.1	114	0.042	1600
Case IV	*OpenDSS*	*00:00-24:00*	162	222	25.3	175	0.11	1918
	Optimizer	*00:00-24:00*	186	218	9.96	154	0.04	1883
Case V	*OpenDSS*	*00:00-24:00*	177	237	21	112	0.09	1382
	Optimizer	*00:00-24:00*	201	227	8.81	86	0.04	1245

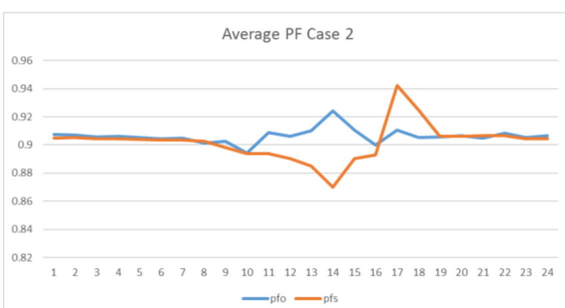
Regarding the THD in voltage and current the table II shows the effect of switching on/off the inverters on the system.

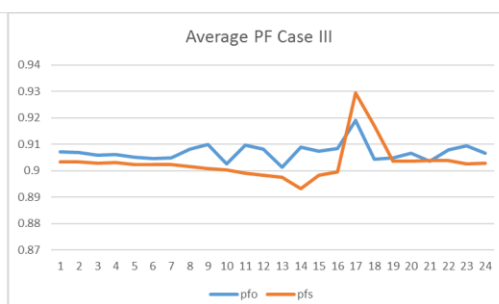
Table II: Summary of THD for all Cases

Case	Simulation Tool	Period of Simulation	THDv (Average)%	THDv max%	THDi (Average)%	THDi max%
Case I	OpenDSS	00:00-24:00	15.4	15.4	26.1	26.1
	Optimizer	00:00-24:00	15.4	15.4	26.1	26.1
	Optimizer	16:00-20:00	15.4	15.4	26.1	26.1
Case II	OpenDSS	00:00-24:00	9.1	9.1	23.8	23.8
	Optimizer	00:00-24:00	13.6	13.6	28.6	28.6
	Optimizer	16:00-20:00	14.5	14.5	26.2	26.2
Case III	OpenDSS	00:00-24:00	9.8	9.8	24.1	24.1
	Optimizer	00:00-24:00	13.7	13.7	26.5	26.5
	Optimizer	16:00-20:00	12.7	12.7	25.3	25.3
Case IV	OpenDSS	00:00-24:00	9.8	9.8	24.1	24.1
	Optimizer	00:00-24:00	11.8	11.8	25.5	25.5
Case V	OpenDSS	00:00-24:00	12.0	15.5	40.0	65.0
	Optimizer	00:00-24:00	16.0	18.2	43.5	72.1

For the effect of the proposed solution on the PF from the utility side is shown in Figure (5.34), the drawn PF when the optimizer allowed to use charging/discharging all the time, the difference between the simulated PF and optimized PF is the inverter of the charger is always constant which is equal 1 and the output PF from the solar charger is 0.95, so the utility will provide the most needed reactive power to the load, it is obvious that the difference during the sun hours where the inverters will provide the real power and the utility will provide reactive power.







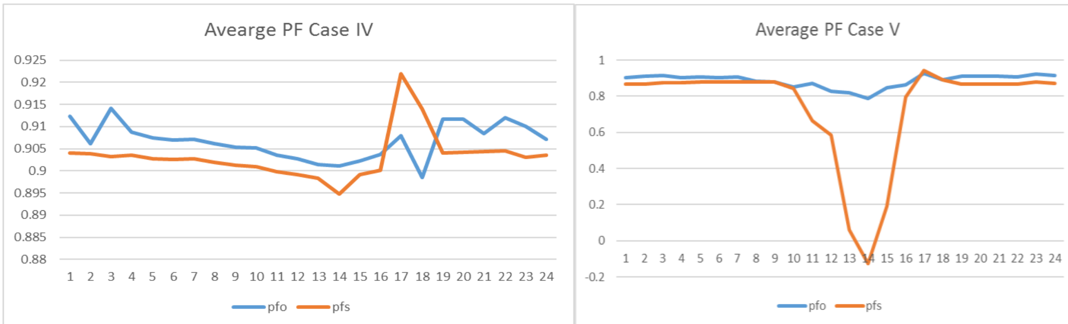


Figure 5 34: Average PF for all cases where the charging and discharging is allowed 24 hours, Blue line is the optimized solution and the orange is the simulated.

Chapter 6

Conclusions and Future Work

6.1 Conclusions

The proposed NLP to formulate optimization problems to minimize the objective function, which indicate increased generated power from a solar system, decreased losses and reduced generated energy from utility. The programing also deals with unbalance voltages between the three phases. A simulation for a power grid was conducted to investigate the line losses and the voltage behavior on the buses. Five cases were studied with/without high penetration of RES and Storage Systems, and discharging/charging periods with different scenarios were conducted and studied. The results show that, the line losses reduced and the generated power from utility were decreased by finding the optimal point of charge of Electrical Vehicle and discharge storage. The results for the four cases were as follows:

1- Case I: the solar penetration was 120% of the load, the programing finds the optimal point to discharge and charge the EV to cover load and achieve the objective function, starting to charging EV from 12:00 until obtaining 20kWh at 24:00 for all EV. It is occurring at the same time where the solar produce peak energy. After setting the charging/discharging period between 16:00-20:00, EV charges from 16:00 till 18:00, the line losses increased by 3% from allowing the charge and discharge all the time. The voltage was balanced and the PVUR is less than 2.6%.

2- Case II: the solar penetration was 50% of the load, the optimizer finds the optimal point to charge/discharge the EV to cover the load and achieve the objective function, also as Case I the simulation was divided to two scenarios of different charge/discharge periods, during the first period, the EV charge starts at 12:00 but the transferred energy for each bus are not equal, this is to keep three phase balance and minimize losses. The second scenario is to allow charge/discharge from 16:00-20:00, the start of transferred energy to EV at the same time, but it varies in quantity from bus to another to maintain voltage balance and minimize losses. The line losses increased by 3% when the charge/discharge is limited.

3- Case III: the solar penetration is 10% and storage system only on bus 7, same as the above cases, the simulation was conducted for two periods, the charging of storage energy in the EV is started from 08:00 till 17:00 and discharged till 23:00, the optimizer covers this energy from the PV system and the behavior of the optimizer is the same for limited period it starts from 16:00 till 20:00 most of transferred energy are from PV system and it start discharging after 17:00 till 19:00. The three phase voltages still balanced and the line losses increased by 0.9% when the optimizer allowed to charge and discharged is limited

4- Case IV: the solar penetration is 10% and storage system only on bus 7, this is extreme case where the charge and discharge is applied to second phase only. The line losses are reduced by using the optimizer to 13%, the three phase voltage still balanced and PVUR is less than 5% in this case. Storage system starts charging the storage system the energy from 9:00 to 17:00 and storage system starts discharge after that to cover the load till 18:00 .

5- Case V: the solar penetration is same as Case I but the load not balanced for the three phases, the generation is reversed without using optimizer, since the charging and discharging is not controlled but by using optimizer the charging of EV starts at the peak of RES generation to minimize the generated power from utility. And the losses also decreased by 23%.

As a conclusion, using this technique will improve the grid performance and to minimize the upgrading cost. By adding cost to the transferee energy from EV to grid may encourage EV users to connect their cars to the network, which may increase profit of owning this type of cars.

6.2 Future Works

Future work may be conducted to study the followings:

1- Three Phase Current Balance.

2- Protection will be added to the boundaries.

3- Cost for the battery will be added to the optimization equations.

4- Cost of tap changer will be added to the optimization equations.

References:

[1] A. S. Anees, "Grid integration of renewable energy sources: Challenges, issues and possible solutions," in *2012 IEEE 5th India International Conference on Power Electronics (IICPE)*, 2012, pp. 1-6

[2] EPRI Electrical Power Research Institute. (2015, Oct.) Home page. [Online]. Available: http://sourceforge.net/projects/electricdss/

[3] https://www.gams.com/

[4] https://www.bloombergquint.com/business/2017/04/24/the-electric-car-revolution-tesla-began-faces-its-biggest-test.

[5] A. N. Al-Shamani, M. Y. H. Othman, S. Mat, M. Ruslan, A. M. Abed, and K. Sopian, "Design & sizing of stand-alone solar power systems a house Iraq," Design & Sizing of Stand-alone Solar Power Systems A house Iraq Ali, 2015, pp. 145-150.

[6] C. Wang and M. H. Nehrir, "Power management of a stand-alone wind/photovoltaic/fuel cell energy system," *IEEE transactions on energy conversion,* vol. 23, 2008, pp. 957-967.

[7] M. Malinowski, J. I. Leon, H. Abu-Rub, "Solar Photovoltaic and Thermal Energy Systems: Current Technology and Future Trends", *Proc. IEEE*, vol. PP, no. 99, pp. 1-15, Apr. 2017.

[8] https://www.eurobserv-er.org/wind-energy-barometer-2017/

[9] GWEC, Global Wind Report Annual Market Update". Gwec.net. Retrieved 2017-05-20.

[10] B. Burger, "Fraunhofer institute for solar energy systems ISE," ed, 2017.

[11] J. Von Appen, M. Braun, T. Stetz, K. Diwold, and D. Geibel, "Time in the sun: the challenge of high PV penetration in the German electric grid," *IEEE Power and Energy magazine,* vol. 11, 2013, pp. 55-64.

[12] M. J. E. Alam, K. M. Muttaqi, and D. Sutanto, "Effective utilization of available PEV battery capacity for mitigation of solar PV impact and grid support with integrated V2G functionality," *IEEE Transactions on Smart Grid,* vol. 7, 2016, pp. 1562-1571.

[13] G. O. Cimuca, C. Saudemont, B. Robyns, and M. M. Radulescu, "Control and performance evaluation of a flywheel energy-storage system associated to a variable-speed wind generator," *IEEE Transactions on Industrial Electronics,* vol. 53, 2006, pp. 1074-1085.

[14] S. Rehman, L. M. Al-Hadhrami, and M. M. Alam, "Pumped hydro energy storage system: A technological review," *Renewable and Sustainable Energy Reviews,* vol. 44, 2015, pp. 586-598.

[15] H. Lund and G. Salgi, "The role of compressed air energy storage (CAES) in future sustainable energy systems," *Energy conversion and management,* vol. 50, 2009, pp. 1172-1179.

[16] Y. Liangzhong, Y. Bo, C. Hongfen, J. Zhuang, Y. Jilei, and X. Jinhua, "Challenges and progresses of energy storage technology and its application in power systems," *Journal of Modern Power Systems and Clean Energy,* vol. 4, 2016, pp. 519-528.

[17] X. Huang, Z. Zhang, and J. Jiang, "Fuel cell technology for distributed generation: an overview," in *2006 IEEE International Symposium on Industrial Electronics*, 2006, pp. 1613-1618.

[18] M. Guerrero, E. Romero, F. Barrero, M. Milanes, and E. Gonzalez, "Overview of medium scale energy storage systems," in *2009 Compatibility and Power Electronics*, 2009, pp. 93-100.

[19] W. V. Hassenzahl, "Superconducting magnetic energy storage," *Proceedings of the IEEE,* vol. 71, 1983, pp. 1089-1098.

[20] M. Quraan, T. Yeo, and P. Tricoli, "Design and control of modular multilevel converters for battery electric vehicles," *IEEE Transactions on Power Electronics,* vol. 31, 2016, pp. 507-517.

[21] M. Kwiecien, J. Badeda, M. Huck, K. Komut, D. Duman, and D. Sauer, "Determination of SoH of Lead-Acid Batteries by Electrochemical Impedance Spectroscopy," *Applied Sciences,* vol. 8, 2018, p. 873.

[22] J. Yu, B. Mo, D. Tang, J. Yang, J. Wan, and J. Liu, "Indirect state-of-health estimation for lithium-ion batteries under randomized use," *Energies,* vol. 10, p. 2012, 2017.

[23] M. Murnane and A. Ghazel, "A closer look at state of charge (SOC) and state of health (SOH) estimation techniques for batteries," *Internet: http://www. analog. co m/media/en/technical-documentation/technical-articles/A-Closer-Look-at-State-Of-Charge-and-State-Health-Estimation-Techniques-.... pdf,* 2017

[24] S.-C. Huang, K.-H. Tseng, J.-W. Liang, C.-L. Chang, and M. Pecht, "An online SOC and SOH estimation model for lithium-ion batteries," *Energies,* vol. 10, 2017, p. 512.

[25] M. A. López, S. Martin, J. A. Aguado, and S. de la Torre, "Optimal microgrid operation with electric vehicles," in 2011 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies, 2011, pp. 1-8.

[26] M. C. Kisacikoglu, M. Kesler, and L. M. Tolbert, "Single-phase on-board bidirectional PEV charger for V2G reactive power operation," *IEEE Transactions on Smart Grid,* vol. 6, 2015, pp. 767-775.

[27] A. Rabiee, H. F. Farahani, M. Khalili, J. Aghaei, and K. M. Muttaqi, "Integration of plug-in electric vehicles into microgrids as energy and reactive power providers in market environment," *IEEE Transactions on Industrial Informatics,* vol. 12, 2016, pp. 1312-1320.

[28] S. F. Abdelsamad, W. G. Morsi, and T. S. Sidhu, "Impact of wind-based distributed generation on electric energy in distribution systems embedded with electric vehicles," *IEEE Transactions on Sustainable Energy,* vol. 6, 2015, pp. 79-87.

[29] A. Ovalle, A. Hably, S. Bacha, G. Ramos, and J. Hossain, "Escort evolutionary game dynamics approach for integral load management of electric vehicle fleets," *IEEE Transactions on Industrial Electronics,* vol. 64, 2017, pp. 1358-1369.

[30] H. V. Haghi and Z. Qu, "A kernel-based predictive model of ev capacity for distributed voltage control and demand response," IEEE Transactions on Smart Grid, vol. 9, 2018, pp. 3180-3190.

[31] W. Wang, W. He, J. Cheng, X. Huang, and H. Liu, "Active and reactive power coordinated control strategy of battery energy storage system in active distribution network," in 2017 32nd Youth Academic Annual Conference of Chinese Association of Automation (YAC), 2017, pp. 462-465.

[32] A. Awad, P. Bazan, and R. German, "Profit enhancement through optimized operation of photovoltaic systems with elastic demand," in 2013 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2013, pp. 1-6.

[33] A. Awad, A. Bazbaz, A. Marabeh, and A. Samamra, "Exploring the impact of EVs on the power grid with high penetration of RES," in *2018 IEEE 12th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG 2018)*, 2018, pp. 1-6

[34] A. Zeinalzadeh, R. Ghorbani, and E. Reihani, "Optimal power flow problem with energy storage, voltage and reactive power control," in Proceedings of the ISCIE International Symposium on Stochastic Systems Theory and its Applications, 2014, pp. 204-210.

[35] P. Lombardi, T. Sokolnikova, K. V. Suslov, and Z. Styczynski, "Optimal storage capacity within an autonomous micro grid with a high penetration of Renewable Energy Sources," in 2012 3rd IEEE PES Innovative Smart Grid Technologies Europe (ISGT Europe), 2012, pp. 1-4.

[36] A. Del Pizzc, L. Di Noia, D. Lauria, M. Crispino, A. Cantiello, and F. Mottola, "Control of OLTC distribution transformer addressing voltage regulation and lifetime preservation," in *2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, 2018, pp. 1002-1007.

[37] N. Mahmud and A. Zahedi, "Review of control strategies for voltage regulation of the smart distribution network with high penetration of renewable distributed generation," *Renewable and Sustainable Energy Reviews,* vol. 64, 2016, pp. 582-595.

[38] M. Ammar and A. M. Sharaf, "Optimized Use of PV Distributed Generation in Voltage Regulation: A Probabilistic Formulation," *IEEE Transactions on Industrial Informatics,* vol. 15, 2019, pp. 247-256.

[39] E. Abraham, H. Marzooghi, J. Yu, and V. Terzija, "A Novel Adaptive Supervisory Controller for Optimized Voltage Controlled Demand Response," *IEEE Transactions on Smart Grid,* 2018.

[40] A. Awad, P. Bazan, R. Kassem, and R. German, "Co-simulation-based evaluation of volt-var control," in 2016 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), 2016, pp. 1-6.

[41] K. Turitsyn, P. Sulc, S. Backhaus, and M. Chertkov, "Options for control of reactive power by distributed photovoltaic generators," Proceedings of the IEEE, vol. 99, 2011, pp. 1063-1073.

[42] A. Gabash and P. Li, "Active-Reactive Optimal Power Flow in Distribution Networks With Embedded Generation and Battery Storage," IEEE Transactions on Power Systems, vol. 27, no. 4, 2012, pp. 2026–2035.

[43] P. Jahangiri, "Voltage and reactive power regulation by photovoltaics in distribution systems," 2014.

[44] C.-Y. Lee, "Effects of unbalanced voltage on the operation performance of a three-phase induction motor," *IEEE Transactions on Energy Conversion,* vol. 14, 1999, pp. 202-208.

[45] A. M. Nour, A. Y. Hatata, A. A. Helal, and M. M. El-Saadawi, "Rooftop PV systems with distributed batteries for voltage unbalance mitigation in low voltage radial feeders," Journal of Renewable and Sustainable Energy, vol. 10, 2018, p. 055302.

[46] J. A. Sa'ed, S. Favuzza, M. G. Ippolito, F. Massaro, "Verifying the Effect of Distributed Generators on Voltage Profile Power Losses and Protection System in Radial Distribution Networks", IEEE/POWERENG Istanbul-Turkey, pp. 1044-1049, May 2013.

[47] N. M. Saad, Z. Sujod, H. Ming, F. Abas, M. Jadin, R. Ishak*, et al.*, "Impacts of photovoltaic distributed generation location and size on distribution power system network," *Int. J. Power Electron. Drive Syst.(IJPEDS),* vol. 9, 2018, pp. 905-913.

[48] P. S. Georgilakis and N. D. Hatziargyriou, "Optimal distributed generation placement in power distribution networks: models, methods, and future research," *IEEE transactions on power systems,* vol. 28, 2013, pp. 3420-3428.

[49] M. Z. Zeb, K. Imran, A. K. Janjua, M. Nadeem, and A. Amin, "Optimal Allocation and Sizing of Solar Panels Generation via Particle Swarm Optimization Algorithm," in *2019 2nd International Conference on Computing, Mathematics and Engineering Technologies (iCoMET)*, 2019, pp. 1-5.

[50] A. Castillo and D. F. Gayme, "Evaluating the Effects of Real Power Losses in Optimal Power Flow-Based Storage Integration," *IEEE Transactions on Control of Network Systems,* vol. 5, 2018, pp. 1132-1145.

[51] P. Pillay and M. Manyage, "Definitions of voltage unbalance," *IEEE Power Engineering Review*, vol. 21, 2001, pp. 50-51.

[52] IEC Standard Voltages, IEC 60038 Ed. 7, June 2009.

[53] A. Nguyen, M. Velay, J. Schoene, V. Zheglov, B. Kurtz, K. Murray, J. Kleissl, "High PV penetration impacts on five local distribution networks using high resolution solar resource assessment with sky imager and quasi-steady state distribution system simulations", *Solar Energy*, vol. 132,2016, pp. 221235.