ANALYSIS AND ENHANCEMENT OF THE DISTRIBUTION NETWORK BY SHARING RENEWABLE ENERGY

2023
MASTER THESIS
ELECTRICAL-ELECTRONICS ENGINEERING

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Prepared as
Master Thesis

KARABUK
February 2023

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Omar Mohammed Raheem AL- ALNUAIMI

ABSTRACT

M.Sc. Thesis

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Institute of Graduate Programs
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February 2023, 128 pages

Iraq's electricity generation in general depends on natural gas, fossil fuels, and oil that accounts about 97%. In accord with the International Energy Agency, the electricity generation increased from 64.75 TWh in 2015 to 97.26 TWh in 2021. With an annual population increase of more than one million people, the electricity demand for Iraq is expected to increase double between now and 2030. There is a significant gap in distribution network system of Iraq, including interruptions and the daily shortages of electricity. Iraq has enormous potential of renewable energy resources and can significantly increase the portion of them in the producing electricity. The penetration of renewable energy to distribution network systems with its advantages has also drawbacks. Renewable energies exhibit power fluctuation, high nonlinearities, changing dynamics, and uncertainties. Therefore, it is required to provide a stable operation and reliability of the power system while integrating renewable energy into the distribution network of the utility grid.

In this master thesis, a study of a low voltage distribution network operation using renewable energy is considered for 11 kV feeder with 3.5 MW load of Baghdad city. Electric Transient Analysis Program (ETAP) is applied to analyse a distribution network including such parameters as load flow, drop voltage, power losses, harmonic analysis, and active power. The distribution network analysis process is executed to evaluate the state and operation of existing system under various load operating cases. Simulation's results in ETAP show that using PV energy can reduce overload and power losses in a distribution network.

Key Words : Distribution network, Renewable energy, ETAP, Load flow, Harmonic analysis, Harmonic filter.

Science Code : 90513

ÖZET

Yüksek Lisans Tezi

YENİLENEBİLİR ENERJİ PAYLAŞIMIYLA DAĞITIM ŞEBEKESİNİN ANALİZİ VE GELİŞTİRİLMESİ

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Şubat 2023, 128 sayfa

Irak'ın genel elektrik üretimi, yaklaşık %97'sini oluşturan doğal gaz, fosil yakıtlar ve petrole bağlıdır. Uluslararası Enerji Ajansı'na göre, elektrik üretimi 2015'te 64,75 TWh'den 2021'de 97,26 TWh'ye yükseldi. Yıllık nüfus artışı bir milyondan fazla olan Irak'ın elektrik talebinin bugünden 2030'a kadar iki katına çıkması bekleniyor. Irak'ın dağıtım şebeke sisteminde, kesintiler ve günlük elektrik kesintileri de dahil olmak üzere önemli boşluklar var. Irak, muazzam bir yenilenebilir enerji kaynakları potansiyeline sahiptir ve bunların elektrik üretimindeki payını önemli ölçüde artırabilir. Yenilenebilir enerjinin dağıtım şebekesi sistemlerine girişinin avantajları yanında dezavantajları da bulunmaktadır, yanı, güç dalgalanmaları, yüksek doğrusal olmama durumlar, değişen dinamikler ve belirsizlikler. Bu nedenle, yenilenebilir enerjiyi şebekenin dağıtım ağına entegre ederken, güç sisteminin kararlı bir şekilde çalışmasını ve güvenilirliğini sağlamak gerekmektedir.

Bu yüksek lisans tezinde, Bağdat şehrinin 3,5 MW yüklü 11 kV fideri için yenilenebilir enerji kullanan bir alçak gerilim dağıtım şebekesinin işletilmesi üzerine bir çalışma ele alınmıştır. Elektrik Geçici Analiz Programı (ETAP), bir dağıtım şebekesini yük akışı, düşme gerilimi, güç kayıpları, harmonik analizi ve aktif güç gibi parametreleri içeren analiz etmek için uygulanmış. Dağıtım ağı analiz süreci, mevcut sistemin çeşitli yük çalıştırma durumları altında durumunu ve işleyişini değerlendirmek için yürütülmüş. ETAP'taki simülasyon sonuçları, PV enerjisinin kullanılmasının bir dağıtım şebekesindeki aşırı yükü ve güç kayıplarını azaltabileceğini göstermektedir.

Anahtar Kelimeler : Dağıtım ağı, Yenilenebilir enerji, ETAP, Yük akışı, Harmonik analiz, Harmonik filtre.

Bilim Kodu : 90513

ACKNOWLEDGEMENT

Firstly, thanks are to God who helped me completing this work, helped me, and gave me the patience to bear all the hardships, so I thank God first and foremost.

Thanks are extended to my supervisor, Prof. Dr. Ziyodulla YUSUPOV, who was like a father, professor, teacher, and role model in all steps of my work. Thanks for your time throughout the preparation of this thesis.

Thanks a lot to my mother, she would not stop encouraging me every day to complete my studies, she was praying to ALLAH for me and supported me. Without her prayers, I would not have achieved this achievement.

Many thanks to my father who passed away, may Allah have mercy on him, it was his wish to see me complete my studies and this journey.

Thank you very much my dear wife, my soul, and for all the sacrifices you made for me, patience, and support. She was the beautiful thing in difficult circumstances.

Special thanks to my children, my heartbeat, and my love (Ibrahim, Yusr, Hassan, Yunus) who, despite their young age, applauded me for every success and their innocent prayers.

Thank you, my sister (Hawraa), who helped me when I needed someone to support me in resolving my issues. My brothers and sisters, friends and colleagues, who stood with me in this work and provided me with advice and guidance, and all the teachers, students, and everyone who mentioned me and prayed to God to grant me success, thank you.

And my last supplication is that praise be to God, Lord of the worlds.

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SYMBOLS

ρ : Air Density

σ : Standard deviation

ω_0 : Fundamental of the power frequency

w_r : Rotational speed

λ : Tip Speed Ratio

θ_i : Phase angle

C_P : Turbine Power Coefficient

P : Active power

Q : Reactive Power

R : Resistance load

L : Inductance

C : Capacitance

ABBREVIATIONS

cov : Covariance

log : Logarithmic

var : Variance

ALCA : Average Linkage Cluster Analysis

MOE : Ministry of electricity

IEA : International energy agency

kVA : Kilo volt ampere

kW : Kilo watt

DN : Distribution Network

DG : Distribution Generation

ETAP : Electric Transient Analysis Program

THD	: Total Harmonics Distortion
IEEE	: Institute of Electrical and Electronics Engineers
IEC	: International Electrotechnical Commission
PCC	: Point of Common Coupling
SLF	: Single Line Filter
SVC	: Static Var Compensator
MV	: Medium Voltage
LV	: Low Voltage
MPPT	: Maximum Power Point Tracing
CHP	: Combined Heat and Power
GE	: General Electric
IGC	: Iraq Generation Capacity
SLD	: Single Line Diagram
PSO	: Particle Swarm Optimization
AVR	: Automatic Voltage Regulator
GFEC	: Generation with a Front-end Converter
DFIG	: Double-Fed Induction Generator

PART 1

INTRODUCTION

1.1. MOTIVATION AND BACKGROUND

Electric power systems generally consist of main part (generation units, transmission system, distribution system, costumer load) and a power grid that connects them. The goal of the power grid is to transfer electric power from production to purchasers while maintaining the reliability of power quality and voltage quality for all customers (for both production and distribution). Old energy systems relied on traditional fuels to produce electricity with central units away from the consumer. There are several reasons for introducing new products and diversifying sources of energy production. The first reason is the open market for energy production in many countries. [1,2].

Iraq is one of the countries in which the energy sector faces several issues.

1. Old power stations.
2. Reliance on conventional fuels in production by 97%.
3. Poor percentage generation from renewable energy despite its possession of sources such as wind in mountainous areas, solar power, and river sources.

All these reasons lead to interruptions in the supply of electricity to customers pushing them to depend on separate small generators to compensate the outage supply from the main grid. Promoting household use the renewable energy in Iraq is an fundamental factor to improve and develop the energy sector [3].

The combination of Photovoltaic (PV) system in power distribution network (DN) is important in enhancing voltage, reducing the power demand, and feeder losses (especially when choosing the appropriate size and location) in distribution networks that reach 50% conforming to International Energy Agency. This issue is what the energy sector in Iraq suffers from. Most of the previous studies ignored enhancing renewable energy usage and its impact on the distribution network and focused on increasing production using conventional power stations [4].

The integration of renewable energy with power distribution systems in small quantities does not have a serious impact, but the increase in diesel generator (DG) penetration has a considerable effect on the operation of DNs, as the specifications of distribution network (DN) are different from the characteristics of transmission lines for the following reasons:

1. The DN works in radial-topology.
2. Significant imbalance may exist.
3. The DN has a larger R/X ratio than the transmission line.

Where the power system is designed to supply in one direction from HV to LV side, the installation of the DG is near the LV consumer side, and injection of a large amount of DG leads to bi-directional power flow, which has a drawback on the stability of distribution system [4].

It is necessary to plan and ensure the stable operation of the smart distribution network, so there must be an analysis of the relation betwixt the incorporation of DG and the behavior of the DN. Wherefore, power flow analysis uses a computer program designed for this purpose to understand the attitude of the system over some time and make sure that the power system satisfies the performance. This includes knowing the amount of power equipped for the loads like over voltage, under voltage, power factor, active power losses, reactive power losses, etc. before and after the PV system penetration. In addition, the effect of harmonics due to the use of power-electronic devices likes inverters in the PV system and finding solutions to them [4].

1.2. PURPOSE AND CONTRIBUTION

The thesis's aim is to analyze and improve distribution networks and simulate a list for one of the areas in the Baghdad, Iraq using Electrical Transient Analysis Program (ETAP). The implementation of this purpose included the following topics:

1. Simulation and analysis of Single Line Diagram (SLD) for distribution network (DN).
2. Contribution in enhancement the DN by reducing active power losses (W), reactive power losses (kVAR), and feeder load by injecting the PV system.
3. Contribution in enhancement of DN voltage profile after linking different capacities of the PV system.
4. Analyzing the time domain power flow before and after the penetration to achieve the best operation condition and show the sensitivity of significant change parameters affecting the PV system connected with distribution network based on ETAP software.
5. Analyzing the effect of harmonics, after PV system injection, on distribution networks for the case study based on ETAP software.
6. Designing (LC) filters to reduce the effects and losses from the harmonic phenomena of voltage waves that occur for the distribution network based on ETAP software.

1.3. METHODOLOGY

The distribution networks of the case study contain an integrated number of power transformers, circuit breakers, busbars, transmission lines and loads, etc. The methods that were applied to this study illustrate the following list:

1. Studying the distribution networks' structure and network configuration
2. Considering power flow methods and applying Newton-Raphson theorem to analyze power flow of distribution network.
3. Using ETAP software to analyze harmonics before and after integration of PV systems.

4. Designing the LC filter on ETAP software.

1.4. LITERATURE REVIEW

According to [5], the author made a simulation of a skyscraper's distribution network by using a radial network and Ring main network system, also compared the best feeding method to reduce voltage drops, losses, and make the distribution network more reliable. It turns out that the ring connection method is better regardless of the cost.

The author in [6] analyzed and monitored the power system of one of the transmission and distribution lines with a voltage of 132 kV in Gujranwala, Pakistan, and the six transformers contained in this line supply 11 kV. The editor chose a transformer that supplies 6 feeders with a voltage of 11 kV, considering that this line contains different loads, domestic and industrial loads, in addition to non-linear loads like furnace load. The monitoring depends on dividing the power system into three parts; the first part (A) is the secondary part that is connected to the power transformer, the second part (B) is at the side of primary distribution, like 11 kV feeder, and the third part (C) is the non-linear loads as furnace load. The purpose is to make an analysis that includes power factor, required load, active power and reactive power, and Total Harmonic Distortion (THD) for each part starting from sockets, circuit breakers, transformers, capacitance, cables, etc. The result of the analysis and monitoring by doing the simulation showed what the line needs to improve at the present for conventional grid and smart network in the future.

The author relied on a procedure to reduce losses in Naypyitaw, Pyinmana Township, the distribution network after using a network reconfiguration system that operates on a radial voltage 33/11 kV, it allowed the delivery and transfer power to the load through more than one feeder. The process of reducing losses in the distribution network depends on what is known as network reconfiguration, which is a process based on linking the load to more than one branch, and after that, it is a logarithmic process that is the procedure of opening and closing to choose the line with the least loss, also change position from one line to another by using ETAP to perform logarithm sequence, network reconfiguration process in the radial system reduced the losses by 19.4% in the case study [7].

The editor in [8] relied on the study of distribution networks that deals with medium and low voltage, from a voltage of 11 kV and less value, considering it the last step that provides the consumer, focuses on reducing the losses after comparing the use of more than one type of Aluminum Conductor Steel-Reinforced cable (ACSR). This analysis was carried out using ETAP. An analysis was conducted on a distribution network containing 11 busbars, 33 line sections, and 23 power transformers with different capacities. After making a comparison for all types and knowing the losses and costs for each type, the appropriate type of ACSR for each line was re-selected without focusing on voltage drop as well as improving the rate used in connections by any addition like capacitance or filter. The study just replaced conductors with the type that has least losses and cost.

In [9] the authors relied on a study that discussed the effect of injection and penetration of solar and wind energy into distribution networks based on ETAP software. Percentage of renewable energy penetration on the distribution network varied from 15% to 30% and finally 50 %. They showed that the increased penetration of solar and wind energy at high rates leads to reverse power flow due to the increased injection current in the feeder, in addition to an increase in the demand load on the transformers. The increment in renewable energy’s amount in DN sometimes leads to the collapse of the system, as it was founded on the fact that if the percentage is more than 50% of the total load in the event of a loss due to a specific circumstance like the presence of clouds or low wind speed, the system could not be compensated by the main network after the frequency drops in a harsh condition, as the editor concluded that the best percentage is 30% for renewable energy in the main DN.

A simulation of the renewable energy’s effect on distribution networks was carried out in terms of calibration of the relay coordination by protection relay. The authors worked on two scenarios, the first one is the injection of renewable resources under 20%, and the second one up to 20%. Case study on 33 kV feeders and 10.45 MVA load. Total harmonic distortion reduced to less than 20% when any type of RE is added, as it is an increase that will lead to a reverse turn and increase the sensitivity of the error tracking sensor, thus losing load handling to the consumer [10].

In the study [11], it was focused on the analysis of a distribution network operating at 11 kV located at the Indian Institute of Technology Gandhinagar. The study was done on the effect of adding an Automatic Power Factor Correction (APFC) as well as adding renewable energy and their effect on the distribution network. It was concentrated on the effect of adding a power factor enhancer by injecting what is known as reactive power that leads to reducing voltage drop, losses, and power transformers, resulting in reduced losses in the distribution system, consistent with an increment in load on the main grid. Moreover, PV system compensates for these losses and achieves more stability, where PV system represents active power and APFC represents reactive power.

The authors in [12] focused on the effect of dynamic switching between feeder substations in a distribution network when PV system is penetrated in different seasons at peak loads. The authors used ETAP and PSS-Sincal to make a simulation and the selection was ROSS Plains (RP) substation network to model. It is in Townsville area of North Queensland in Australia and the result found that the process of dynamic switching between feeders of the substation can reduce voltage rise and peak load on the feeder add to prevent reverse power flow and increase the utility of solar energy utilization and its uniform distribution, the result is beneficial for the consumer and the utility.

The study of [13] focused on the rise voltage phenomena of installing the residential PV system at low voltage for a single-phase 3-wire system in the distribution networks which are widely used in Japan. Reduce the impact of growing the voltage on the low voltage busbar according to the impedance wire and its distance from the distributed network by concerning the PV site. The second scenario restricts the power consumption by constraining the total power from the PV site's redistribution, thus achieving more stability in terms of supply voltage and power flow.

In [14] , an approach called Dynamic Voltage Restorer (DVR) was used, which is summarized by using the logarithm in Low Voltage (LV) DNs on the secondary side of power transformers in the case of fixed tap transformer, this process allowed to prevent high voltage drop in all network nodes as well as prevent damage to the network in the case of injecting a large amount of PV, this path also shows a condition of the technology of art with constant voltage organization via the internet without the necessity for connection links, that are presently not obtainable in LV networks. It is completed by inserting small amounts of P and Q into system in disparity to the current modes.

The researcher in [15] worked on linking what is known as hosting capacity to a large scale of photovoltaic in distribution networks without deteriorating energy quality in terms of voltage and thermal restrictions resulting from penetrating large amounts of photovoltaic. This work was explained by a collection of substitution with a larger conductor size than the distribution feeder as well as a compensator and voltage level upgrade obtained through power flow. The calculations, moreover, found that updating the voltage level in the distribution networks is useful and practical in increasing the quantities of solar energy as well as reducing losses.

The study [16] is an investigation that was made on the behavior and effect of using Transformer Less TL-PV inverters on short-term voltage stability in low-voltage distribution networks with large integration of using TL-PV units and distribution network stabilization drivers. After simulation, control methods for LV Ride-Through show the capability that TL inverters can stop voltage breakdown in highly PV penetration in distribution networks. Additionally, the results of different levels of reactive power insertion by TL inverters were shown. Due to the high ratio of R/X of system, the procedure of recovery of voltage may be less effective by various scales of reactive power insertion.

An investigation of a distribution network with a voltage of 11 kV and impact of voltage when PV penetrates the distribution network was carried out in [17], the first scenario was implemented without focusing on a specific control while the second scenario used a smart inverter that controlled the voltage/var. MATLAB was used to simulate, to find the results and differences. The work is summarized by controlling the smart inverter by increasing the reactive power when load increases and voltage decreases when voltage is high on the feeder and vice versa.

The study [18] focused on the configuration of a feeder in a distribution network by changing the switching tie with maintaining the radially of the network by using Particle Swarm Optimization (PSO). The test was done IEEE 33 busbars networks standard and gave the best topology for this network as the result showed maximizing voltage profile and minimizing losses in the distribution system.

The study [19] focused on the impact of green energy and its future of power quality on distribution networks, how to reach the reliability of distribution networks in China, and plans with the increasing demand for renewable energy. It focused on finding the appropriate solutions by considering the distribution network is the part that is linked and giving proposals to study and develop the reliability of distribution networks in-line with the development in simulation and communication software technology.

This work [20] was simulated by using MATLAB to develop voltage profile, quality of power flow, along load line from the beginning to the feeder end by using Dynamic Voltage Restorer (DVR) technique on voltage supply line of a DN of 11/0.4 kV, and it also showed some advantages of using this method under steady-state operation for low voltage 3-phase balanced loads in the distribution network.

A simulation was made by using the ETAP in [21] to design and analyze an urban distribution network in India. The study focused on reducing losses through two cases; first case reduced losses by 19.34% while the second case used feeder bifurcation that reduced losses by 26.87%. Also, the cost-benefit analysis of the feeder for two scenarios was carried out.

The researcher in [22] focused on the extent of the influence caused by permeation of distributed generators on power systems in terms of power flow and fault current based on a simulation by ETAP through a distribution network containing 46 busbars, then a comparison of the integration of distributed generation with different long distances in the feeding unit, the researcher concluded that the distribution generators affect the fault currents careless of location of the fault, nonetheless, the fault current contributed from the distribution generators relies on where the fault is existed, as this contribution reduces the fault current if the penetration occurred in the middle of the feeding point.

The researcher in [23] investigated the effect of location and technology used in distribution generators on the stability of power system voltage along with the value of power losses, after taking a distribution network containing 33 and 65 busbars in Brazil. The appropriate location to connect the sources of the distributor generator is determined through the model analysis of the contributing factors, and then this type of participating factor can be used in evaluating the impact of distribution generator technology on power line. The analysis reached a significant impact on the stabilization of power system voltage and power losses due to location and technology of the distribution generator used, and in some cases, its presence leads to deterioration in stabilization of power losses and voltage.

The researcher [24] analyzed the effect of penetrating a medium size of power from solar cells through the side of low voltage on main network's side. Because the presence of inverters that convert the electric current from DC to AC, a mixture will occur between power of microgrid and power system, the analysis relied on ETAP for the system's state before and after the combination of PV system with the main grid, as well as the design of bank filters to absorb harmonics that protect the system from abnormal operating conditions that result from the PV system's inverter.

The author in [25] investigated power converter and the techniques used in distribution generators, as well as the impact of injecting distribution generation on power system and strategy used to enhance and improve this connection, the protection was also discussed since power converters are the core of photovoltaic and wind energy systems. Since it is beyond discussion that photovoltaic and wind energy have a considerable influence on power system, the investigation concluded to put several control techniques on distribution generators to reach reliability and flexibility in the operation of the energy entering the system. With limitations in the connection, they can be addressed by controlling the inverters in the distribution generators. The researcher concluded that the distribution modules give the network flexibility, as they cannot work by connecting on-grid or islanding. Whereas the distribution generators can restore transmission lines in case of an outage and use it in case after maintenance from failure.

The researcher in [26] made a comprehensive development of the Model Predictive Control (MPC) of Loop Power-flow Controller (LPC) for the operating state response time and power output variables from distribution generators under safety conditions and over multiple operating periods, 2 test systems containing 132 and 32 nodes were utilized to confirm the precision and validation by using MPC model. The researcher concluded that the control of power flow is done by LPC to reduce the effect of increased penetration by distribution generators, as power flow control plays a significant part in balancing loads on feeders, regulating voltage, and allowing increased penetration and participation by distribution generators.

The researcher in [27] conducted a comparison of a microgrid in several studies in the field of energy management on a small scale, and its usefulness, such as minimizing power losses in distribution networks and simplifying control operations. Where many previous studies are compared, including the study of the network structure, mode of operation, energy storage systems, types of loads, etc., all these topics must be included in order to achieve the researcher obtaining the ideal analysis, knowing the strengths and weaknesses of each study, and determine future studies clearly, depending on the statistical evidence of each of them. This review enables researchers to choose their targeted studies and easily examine the latest advances in microgrid management according to this review.

The researcher in [28] designed a microgrid which includes a wind turbine, a photovoltaic system, storage units, a small generator, industrial loads, and cables in a Chinese island by using ETAP and simulated it as on-grid system. Additionally, the system's stability analysis was done in the case of a disturbance occurred in some parts of the microgrid. The researcher summarized that the storage unit system can support the power feeding in the case of a disturbance in wind power and the photovoltaic system. The storage system also improves the low voltage that caused by disturbance through the flexibility of switches under various operating conditions in a micro-grid.

In [29] the researcher analysed what is known as power flow analysis by using ETAP on a distribution network consisting of 33 busbars with distribution generators. Various scenarios were simulated to know the appropriate size and location of the distribution generators to reach the voltage profile and least losses of the system, where the researcher showed that choosing an inappropriate location may cause some damage to the system with regard to increased losses and voltage fluctuations. The researcher proved that choosing an appropriate size and location of the distribution modules has a great benefit in terms of preserving the amount of power perfectly and thus reducing production costs.

The author in [30] focused on the effect of multi-source loads on the distribution networks. In order to study and access this effect on the distribution network, the researcher created a hybrid output model of the distributed generators consisting of solar panels, a wind generator, and an electric vehicle. The first step is analysing output characteristics, then the simulation's output of the hybrid model demonstrated its effectiveness and reliability, which can provide ideas for planning distribution networks in the future and managing energy processes, as well as an active distribution network that adapts to the multi-source load.

The researcher in [31] used rooftop solar cells merge renewable energy with the smart grid through a simulation using Simulink in MATLAB to illustrate the impact of expanding penetration of this type on LV network's side. The increase in penetration distribution networks leads to issues such as reverse power flow, voltage fluctuation, reactive power, and increase losses. The simulation's result proved that these issues can be mitigated by using D-STATCOM device.

The researcher in [32] discussed the effect of integrating solar cells on the end-of-line voltage and the resulted losses in case of using distribution networks using radial configuration. The researcher also assumed that the solution is the possibility of reducing losses, improving voltage, and increasing the incorporation of solar energy in DNs by using Loop configuration method. Seven different loop and radial scenarios were implemented using variable values and solar capacity for each in IEEE-33 busbar. The comparison was made based on the MATLAB/Simulink. The result showed the loop use of the radial rings reduces the effect of overvoltage and power losses and leads to expand the permeation of solar cells in power grid.

The study in [33] presented a new control strategy of a three-phase 4-wire inverter that is connecting the grid to effectively benefit from renewable energy resources like wind and solar energy, where inverter works individually or in combination to defeat the unbalanced impacts of linear and non-linear loads to compensate for the current load, compensate load voltage, and compensate active power. The simulation has done using MATLAB/Simulink. The inverter injects active power from renewable energy into the network and thus improves the voltage. The role of the fourth line which is neutral comes to prevent the reverse flow by making the neutral current equal to zero. As for the harmonics resulting from the injection, it is reduced to improve the quality of the power via harmonic filter.

1.5. THESIS STRUCTURE

This thesis consists of seven parts as follows.

In Part 1, the thesis introduction, motivation problem, and background are described along with a general literature review, contribution, purpose of the thesis, uses of methodology in the work, and thesis structure.

In Part 2, introduction of power system structure and topology of distribution network, together with the complex power method, power flow analyze is made, also power flow methods of the power systems are explained.

The load classification and modeling, harmonics, voltage and frequency quality and regulation are discussed in Part 3.

In Part 4, some explanations are made about distributed generation, definition of distributed generation, technologies of distributed generation, distribution generation and loss reduction, effect of distributed energy sources on distribution network of power systems.

Iraq's power systems, the ratios of electricity generation and energy production, the issues that it suffers from and causes interruption from main grid to customer, the study of renewable energy resources in the Iraq region, and the recommendations that should be taken to improve the power system have considered in Part 5.

In Part 6, description of the case study in terms of single line diagram, load profile, distribution network component of the case study, distribution network analysis using ETAP, load flow analysis, harmonic analysis, results, and discussion have presented.

Finally, in Part 7, conclusion, recommendation, and future work are given.

PART 2

DISTRIBUTION NETWORK SYSTEM

2.1. INTRODUCTION

Power systems are developed to generate and transfer electricity produced from large generating stations and deliver it to consumer that is in forms of industrial, commercial, and residential demand. The structure of power system is shown in Figure 2.1.

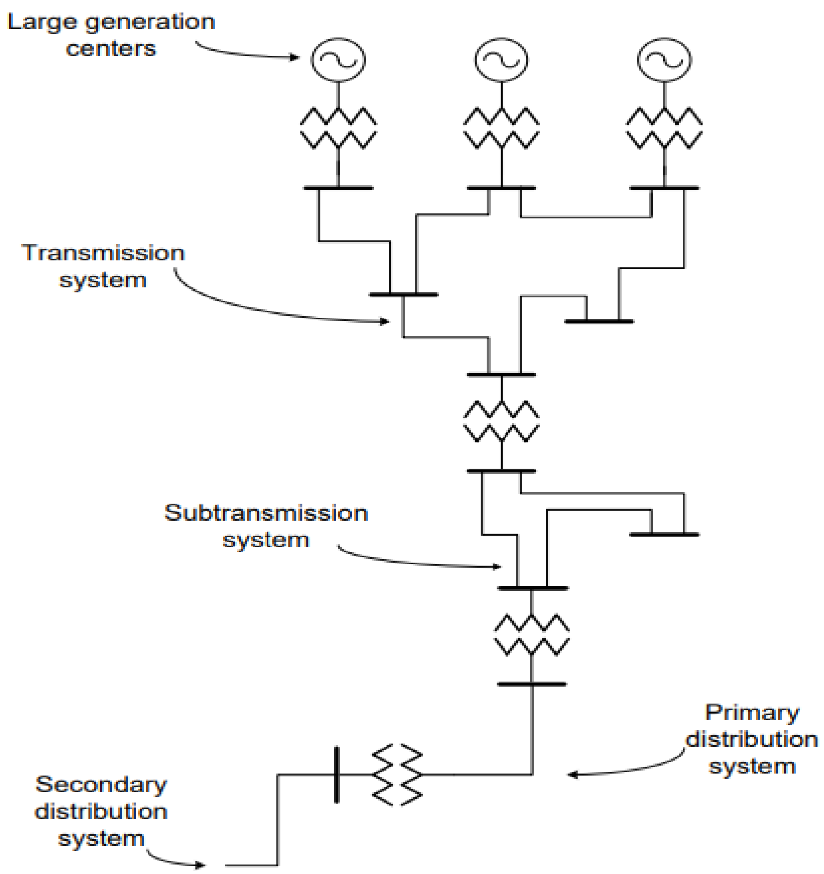


Figure 2.1. The structure of power system [34].

2.2. NETWORK DISTRIBUTION SYSTEM STRUCTURE AND TOPOLOGY

2.2.1. Network Distribution System Structure

The DN system composed of the main parts as shown in the Figure 2.2, which will be briefly described here [34]:

Relay: The Rely protects the feeders and the system devices from damage by ordering command to the circuit breakers to cut off the current resulting from the fault.

Re-closer: Automatic recirculation is a device that protects equipment and devices in a distribution system by sensing overcurrent and interrupting fault current. Then, reset the line automatically when the error is gone. If the fault is permanent, the fault is isolated from the main circuit parts.

Circuit Breaker (C.B): A high current-device which automatically separates the electrical circuit from the load when faults occur. It also facilitates the protection of devices from additional damage, also people from injuries. It is rated according to voltage and short circuit current, and it takes different forms such as air-blast C.B, vacuum C.B, and oil C.B [35].

Fuse: It is a device that contains a metal wire that melts when a large current passes through it or a short circuit occurs, a fuse protects secondary circuits of low-power transformer. They come in different forms with low or high voltage and are made of metals such as silver, zinc, copper, tin, etc.

Sectionalizer: It is a device that isolates the fault on the line segment and protects it from the disturbances that occur to it. It is very sensitive to any increase in current above the specified value. Then it is activate using a recloser.

Renewable Energy: Independent Power Produced by the consumer side, which referred to (IPP), also called distributed power that come from renewable energy resources as PV system, wind power, microturbine, and biomass.

Capacitor Bank: An on-site source of reactive power. It corrects the power factor, implement voltage regulation, and minimize system losses. In general, the capacitor bank is mostly a three-phase system and is placed in the distribution branch networks or through the intermediate points of the lower circuit lines [34,36].

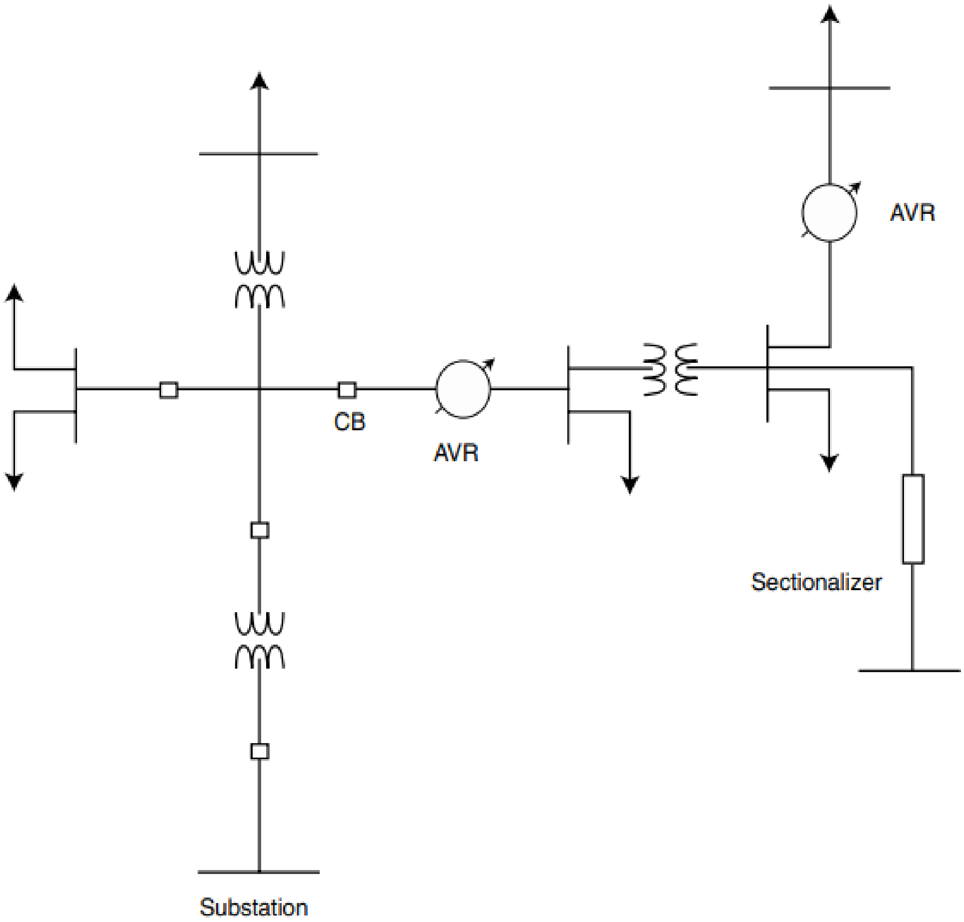


Figure 2.2. Structure of Network Distribution.

2.2.2. Distribution Network System Topology

Distribution networks are designed as a link between transmission system and costumer in a way that allows the flow of power in one direction from high to low voltage levels. There are three types of network connection configuration: radial, Loop, and Network configuration. Each connection constitutes a specific arrangement of the feeder and a distinctive type of connection [36].

2.2.2.1. Radial Configuration of the Distribution Network

This type of connection is vastly utilized, particularly in the feeding of low loads and relatively distant areas. The prime benefit of it is the clarity of work and design, in addition to the low cost of construction. The major drawback of it is the low reliability in the event of faults as the buses at the end of the feeding line will be isolated which means that the busbars are provided from only one side. To minimize the outage period, the main feeders can be preserved by automatic control devices at sub-stations or another areas along the feeder path, Figure 2.3 shows radial configuration [36].

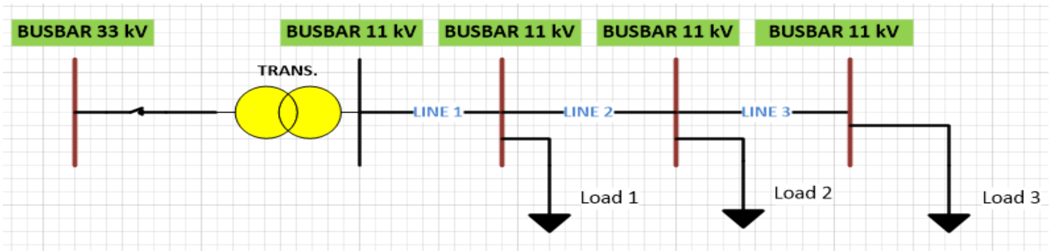


Figure 2.3. Radial configuration of DN.

2.2.2.2. Loop Configuration of the Distribution Network

This system of interconnection is used with service levels of very high reliability and supply continuity. The loop equips two primary feeders. The purpose of this connection is to feed all the busbars and the load from one feeder in the event of an outage or failure. The switching process to change the connected feeder can be done automatically or manually by using a circuit breaker or/and an electrical interlock to block the link between the feeder and the alternative part that is in the event of a failure. The major drawbacks it are the relatively high price and complication by comparing it to radial system [36]. Figure 2.4 illustrates loop configuration of DN.

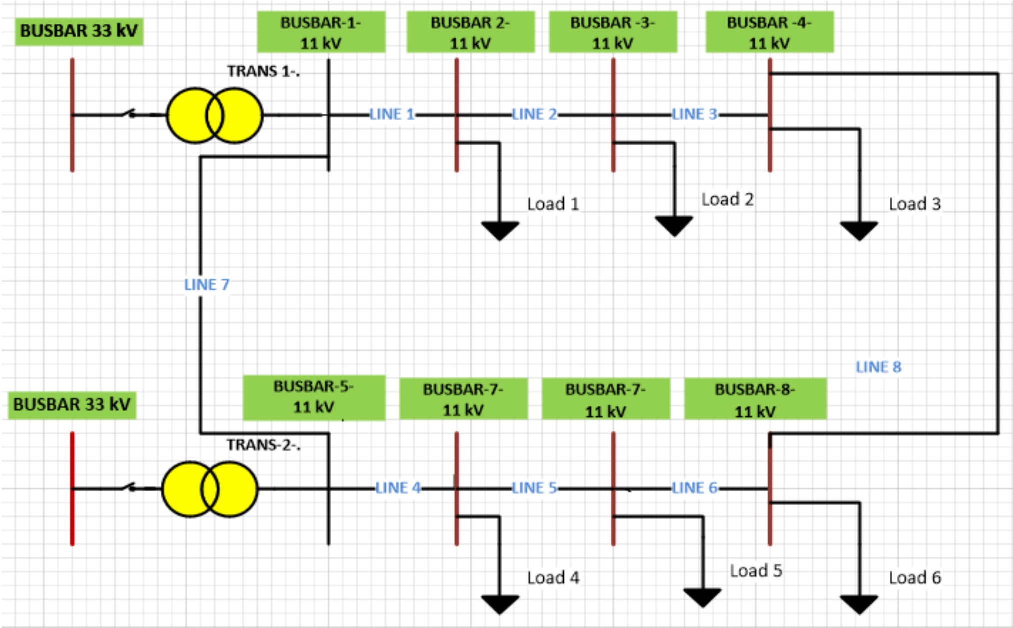


Figure 2.4. Loop configuration of DN.

2.2.2.3. Networking Configuration of the Distribution Network

This type of interconnection is a collection of loop and radial interconnection, or in another way, the growth of one of these connection types significantly leads to what is known as networking in distribution networks. Network configuration is widely utilized in high density loading levels, or in city center where it needs high reliability; it consists of 2 or extra primary feeders through the distribution transformers that, in turn, are preserved by a device to separate them from the feeder or network in case of any failure. In addition, current protection devices are installed in different places to protect the network from problems of expansion and diffusion [36]. Figure 2.5 illustrates the type of networking configuration of DN.

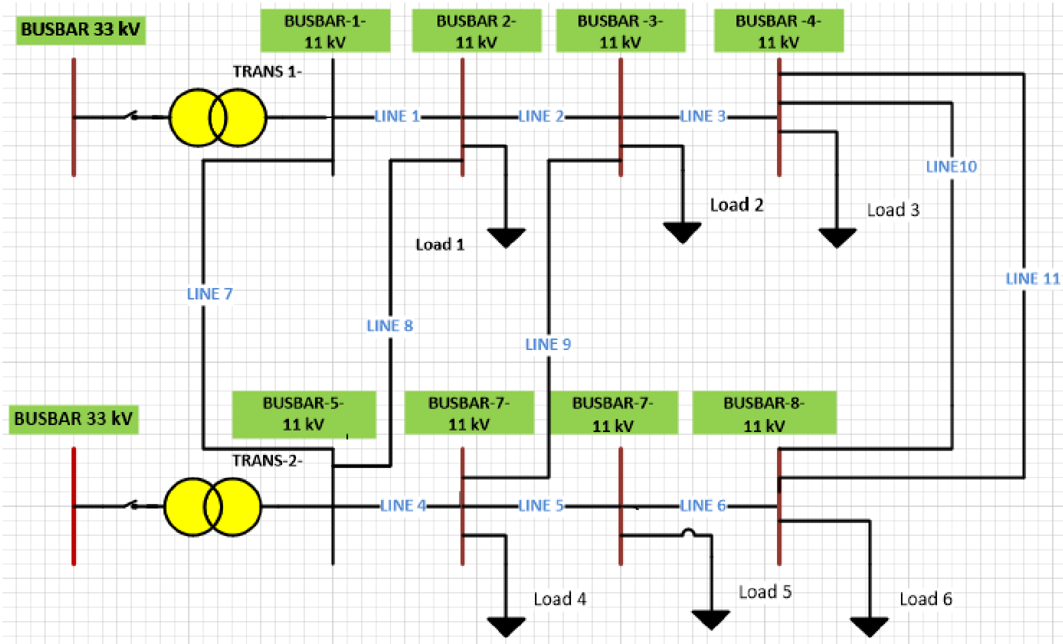


Figure 2.5. Network configuration of the DN.

2.3. COMPLEX POWER METHOD

Calculating the amount of power in an electrical circuit can be done across the injected instantaneous current and the voltage difference across the circuit element. In the simplest terms, we consider a simple load connected to the circuit to represent a generalized load (Z_L) linked to a voltage source V(t) as in Figure 2.6. The sinusoidal representation of the source voltage is given as [35].

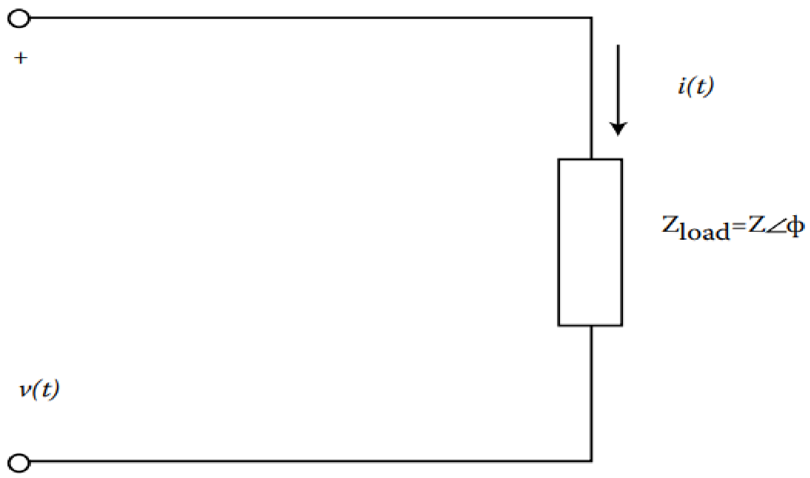


Figure 2.6. Load circuit representations.

$$v(t) = V_m \cos(\omega t) \tag{2.1}$$

And the instantaneous current

$$i(t) = I_m \cos(\omega t - \emptyset) \tag{2.2}$$

Where:

V_m : Amplitude voltage source in Volt.

ω : Angular frequency in rad.

$\emptyset$: Phase shift between voltage and current in rad.

V_{rms} : Root mean square of the maximum voltage as:

$$V_{rms} = \frac{V_m}{\sqrt{2}} \tag{2.3}$$

I_m : Current magnitude.

Complex power is the sum of apparent power and reactive power where:

$$\begin{aligned} S &= P + jQ = VI^* \\ &= VI\, cos\emptyset + jVI\, sin\emptyset \\ &= VI\, (cos\emptyset + j\, sin\emptyset) \end{aligned} \tag{2.4}$$

Simplify and use Euler's method

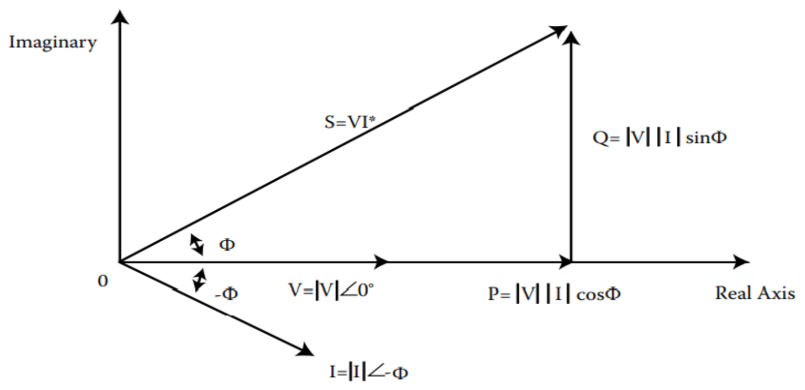


Figure 2.7. Complex power relationship in phase representation.

$$S = VI\, e^{j\emptyset} = VI\, \angle\emptyset \tag{2.5}$$

We can define $I^* = |I|\angle\emptyset$ and rewrite the apparent power equation (2.5) as:

$$S = VI^* \tag{2.6}$$

Also,

$$V = ZI \tag{2.7}$$

That gives,

$$I = YV \tag{2.8}$$

Where $Y = 1\backslash Z$ (admittance)

By substituting (2.8) in (2.6), the result is,

$$S = V(VY)^* = VV^*\, Y^* \tag{2.9}$$

These electric power relations can be illustrated using the phase representation through phase diagram as in Figure 2.7.

2.3.1. Basics of the Power Equations

Typical power consists of three basic components that are resistance (R), capacitance (C), and inductance (L). The following subsections summarize the equations for power losses in terms of voltage and current through these components.

A) Resistive Circuit

The power development across the pure resistive can be expressed:

$$P_r = \frac{1}{T} \int_0^T v_r(t) i_r(t) dt \tag{2.10}$$

By substituting equation (2.1) and (2.2) in equation (2.10), we get,

$$P_{avg.} = V_m\, I_m\, cos^2(\omega t) = \frac{V_m\, I_m}{2} \; [1 + cos\,(\omega t)] \tag{2.11}$$

And then by using (V_{rms}) in (I_{rms})and(I_m)

$$V_{rms} = \frac{V_m}{\sqrt{2}} \tag{2.12}$$

$$I_{rms} = \frac{I_m}{\sqrt{2}} \tag{2.13}$$

We get:

$$P_{avg.} = \frac{I_m}{\sqrt{2}} \; \frac{V_m}{\sqrt{2}} \; [1 + cos\,(\omega t)] \tag{2.14}$$

And the real power losses by the resistance (R) in watt calculated by using:

$$P_r = V I_r = \frac{V^2}{R} = I_r^2\, R \tag{2.15}$$

B) Inductive Circuit

For a circuit containing pure inductance, the reactive power equation can be expressed by the following:

$$P_l(T) = \frac{1}{2} \; V_m\, I_m \; \left[cos\,(\omega t + \emptyset) cos\, \left(\omega t + \emptyset - \frac{\pi}{2}\right)\right] \tag{2.16}$$

$$P_{avg} = V_m V_m \sin \sin [\, 2(\omega t + \emptyset)] \tag{2.17}$$

And the equation to calculate total reactive power losses is:

$$P_{avgxl} = \frac{|V^2|}{X_L} \tag{2.18}$$

Where X_L is the reactive inductance in (Ω).

C) Capacitive Circuit

For a circuit containing pure capacitance, the reactive power development equation can be expressed by the following:

$$\begin{aligned} P_c(t) = v_c(t)\; i_c(t)dt = V_m I_m \cos \left[2(\,\omega t + \emptyset + \frac{\pi}{2})\right] \\ = -VI \quad \sin \sin [\, 2(\omega t + \emptyset)] \end{aligned} \tag{2.19}$$

And total power losses are calculated by using:

$$P_{AVrs} = \frac{|V^2|}{X_C} \tag{2.20}$$

X_C: Capacitive reactance in (Ω).

Finally, based on the configurations of the elements (RLC), whether they are series, parallel, series-parallel connected, active and reactive power are calculated depending on voltage and current distribution in the circuit.

2.3.2. Balanced Voltage to Neutral Connected System

2.3.2.1. Y (WYE) Connected System

Figure 2.8 shows Y-connection method in electrical networks for power systems.

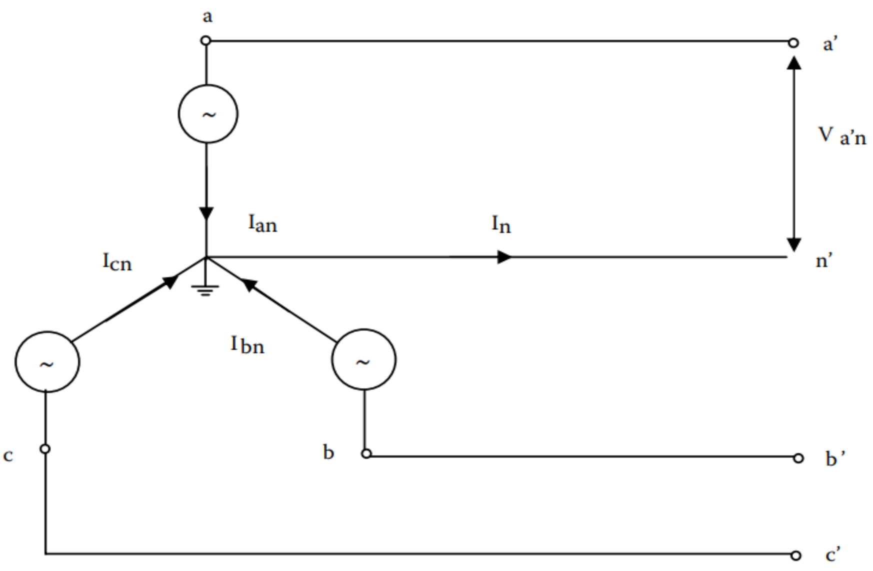


Figure 2.8. Y-connected method.

The terminal voltage (V_{ab}) between (a) and (b) calculated by using:

$$V_{ab} = V_{an} - V_{bn} = V_m\angle 0^0 - V_M\angle -120^0 = m\angle 0^0 - V_M\left[\frac{-1 - j\sqrt{3}}{2}\right] \qquad (2.21)$$

$$V_{ab} = V_m\sqrt{3}\left[\frac{\sqrt{3} + j}{2}\right] = \sqrt{3}\ V_M\angle 30^0 \qquad (2.22)$$

By applying the same steps for the terminal voltage (V_{bc}) and (V_{ca}):

$$V_{bc} = V_{bn} - V_{cn} = \sqrt{3}\ V_M\angle 90^0 \qquad (2.23)$$

$$V_{ca} = V_{cn} - V_{an} = \sqrt{3}\ V_M\angle 150^0 \qquad (2.24)$$

For the Y-connected method:

$$V_{ab} = E_{an}\sqrt{3}\ \angle 30^0 \qquad (2.25)$$

$$V_{bc} = E_{bn}\sqrt{3}\ \angle 30^0 \qquad (2.26)$$

$$V_{ca} = E_{cn}\sqrt{3}\ \angle 30^0 \tag{2.27}$$

In general, the voltage between two lines is equal to the phase's voltage to ground value. In case of current, the value of the line current (I_L) is equivalent to phase current (I_P) value in Y-connected system. If the current is in balance in magnitude and phase, it becomes ($I_a + I_b + I_c = I_n = 0$). Otherwise, in the case of unbalance, the sum of the currents will be ($I_a + I_b + I_c = I_n \neq 0$).

2.3.2.2. Delta (Δ) Connected System

In this system, the line's voltage equals the phase's voltage$|V_L| = |V_P|$. Figure 2.9 shows the Delta connection method.

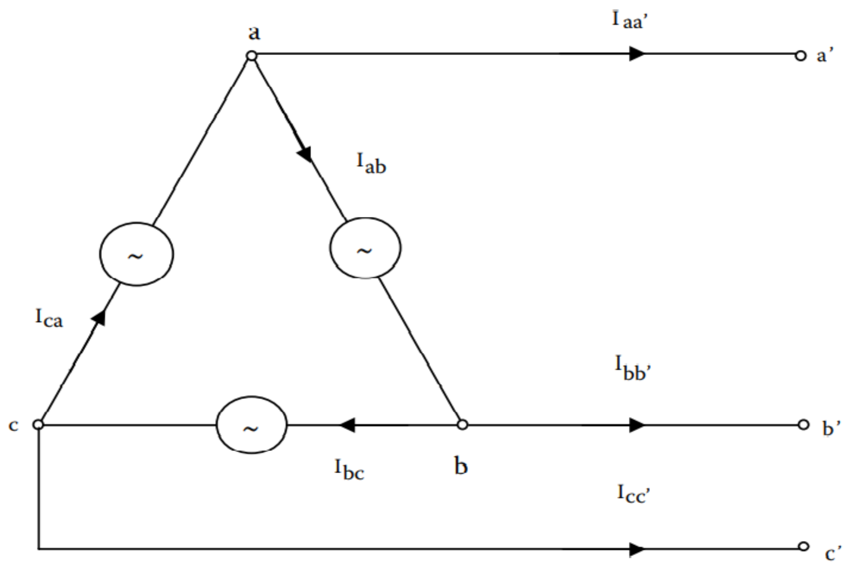


Figure 2.9. Delta connection methods.

The line current is equal to:

$$I_L = \sqrt{3}\ I_P \tag{2.28}$$

To calculate the phase current using:

$$I_{ab} = I_P\ \angle 0^0 \tag{2.29}$$

$$I_{bc} = I_P \angle -120^0 \tag{2.30}$$

$$I_{ca} = I_P \angle +120^0 \tag{2.31}$$

Using Kirchhoff's Current Laws (KCL), the lines currents are:

$$I_{aa'} = I_{ca} - I_{ab} = I_P\sqrt{3} \quad \angle 150^0 \tag{2.32}$$

Similarly ($I_{bb'}$) and ($I_{cc'}$):

$$I_{bb'} = I_P\sqrt{3} \ \angle 30^0 \tag{2.33}$$

$$I_{cc'} = I_P\sqrt{3} \ \angle -90^0 \tag{2.34}$$

2.3.2.3. Power Relationship for Three Phase (Y-Δ-Connected Method)

In the balanced case of a three-phase network, all values of generated current and voltage, respectively, are written in the form of ($V_a(t)$, $V_b(t), V_c(t)$), as well as the current form as ($I_a(t), I_b(t), I_c(t)$). From the previous sections, we reached the relation between line voltage and phase voltage as the equation ($|V_L| = \sqrt{3}\, V_P$). In this case, the three-phase real power values are:

$$P_{3PH} = 3V_P\, I_P\, cos\, \emptyset \tag{2.35}$$

Or we can rewrite as the following:

$$P_{3_{PH}} = \sqrt{3}|V_L|\,|I_L| cos\, \emptyset \tag{2.36}$$

$$Q_{3PH} = \sqrt{3}|V_L|\,|I_L|\, sin\, sin\, \emptyset \tag{2.37}$$

Then, to calculate apparent power:

$$S_{3PH} = P_{3PH} + \quad Q_{3PH} \tag{2.38}$$

In the term line values:

$$S_{3PH} = \sqrt{3}\ V_L\, I_L \tag{2.39}$$

$$P_{3PH} = 3V_P\, I_P\, cos\, \emptyset \tag{2.40}$$

$$Q_{3PH} = \sqrt{3}|V_L|\, |I_L|\, sin\, sin\, \emptyset \tag{2.41}$$

It is possible to analyze and solve the problems of a three-phase circuit for each phase quantitatively when the system is balanced, where one of the phases is taken as a reference, normally it is taken as phase A, and the phases' values of B and C will be found through the phase shaft equivalent (∓ 120) and (∓ 240) respectively. The equivalent of one phase in the circuit represents phase to neutral with respect to voltage and is referred to as line to neutral, but the current represents the line current [37].

2.4. LOAD FLOW ANALYZE

Load flow or power flow, as those two expressions can be used mutually in the standard specifications. As for its definition, it gives solutions to the networks for the state of the stable voltage, current, add to the active power and reactive power through any existing branch or bus in the power system. In general, power flow is used to simulate operating conditions of an actual system that has not yet been established; the reason is due to the time determinants or because it is not correct to expose the element system to damage before making sure that the operating conditions is appropriate. Power flow is amongst the most significant parts of operation and analysis of power systems as well as planning for the reason that the system's elements like transformers, transmission lines, and cables are fixed, and the impedance of the electric power system is also fixed. In any case, the problems of power flow include a constant load (kVA), generator, and tap change transformer. This implies that the relation between current and voltage changes according to load's type, and this also applies to busbar's active and reactive power. The power flow shows the calculation of electrical system's response to a given set of load force and output power [38].

Some devices such as wind turbines and photovoltaic cells are time-varying simulations. Conducting a simulation of power flow by changing the time requires computer programs designed specifically for this type of studies [38].

1. Topics Covered by Power Flow

Power flow solutions to power systems problems cover the following topics:

1. Circuit loads and their elements.
2. Steady state of bus and branch voltage.
3. Active and losses power of power flow.
4. Calibration of power transformers and the effect of changing the conversion ratio on the load.
5. The active and apparent power required for the load, as well as the voltage drop that occurs from the supplied service source.
6. Potential losses (active, apparent) and voltage drop.
7. Voltage drop and an increase above the voltage of the branches, as well as the ends of the bus-bars.
8. Power Factor (PF) improvement requirements.

2. Benefits of Power Flow Analysis

- To achieve the operation of power systems and distribution networks under various operating cases and various loads.
- To plan loads' and generation rate's future growth.
- To calculate the best economic cost of the existing electrical system.
- To know the partial conditions for stability study.
- To find out the value of capacitance or inductance (VAR) that the system needs to keep the voltage within an acceptable value.

3. Power Flow Solutions Requirements

Five important and required properties as solution methods for power flow [39]:

- High computational and processing speed: Especially when it comes to large capacity system with real-time applications.
- Low computer storage: Very important for large systems that required large storage and backup spaces.
- Reliability of the solution: It is necessary to find solutions for various problems in interrupted studies, as well as real-time applications.
- Flexibility: The ability to deal with special and traditional features like adjusting the transformation ratio in transformers to be more suitable for representation in power systems.
- Simplicity: Using an easy code in computer load flow programs.

4. Data Analyze Required

The data required to analyze power systems and distribution networks is generally necessary and can be categorized into:

- Data of system.
- Busbar data.
- Data of electrical load.
- Data of source.
- Data of branches.
- Transferred data.

The data included in power system analysis can be used for other analysis requirements in the power system model as short circuit analysis, stability analysis, and motor starting, so it is necessary to prepare data consistently and comprehensively. Data entry should be entered as accurately as possible because the information is the system's current knowledge. It is also substantial to consider not to enter unconfirmed data. In case of anonymous parameters, they ought not be neglected. Alternatively, it must be written on presumptions based on engineering judgment.

Most computer programs contain libraries of manufacturer components as impedance cable values, impedance transformers, etc. based on the NEC. The use of these libraries is to encourage the selection of unknown input parameters. Care must be taken in choosing to realize the data source and its suitability according to the system's type. Additionally, the possibility of displaying one line graph data is a basic advantage of computer softwares and its usefulness in reducing connection errors [38].

2.5. POWER FLOW METHODS

Because the calculations of power flow problems include non-linear equations, manual solutions are impractical. Before the existence of digital computer programs to simulate the power flow, it was done by connecting an analog board, this board was a simple DC device connected with power system's elements and appeared through a resistance. The calculations were not precise, but the amazing thing is that they were close enough to be able to be applied in practice. At the same time as the development of hardware board, algorithms were also developed to solve network equations efficiently. The Gauss-Seidel logarithms were developed, as the Newton-Raphson theorem. Not long ago, a lot of research has been done to improve this algorithm to make it more powerful and capable of handling large and additional system components. These algorithms continue to evolve and adapt to the requirements of system convergence [38].

There are broad lines for solving power flow problems that can be summed up:

1. Create an initial value for all unknown voltages of magnitude and phase angle.
2. Setting the swing bus's angle. It is considered as the reference for the bus's ignorance angle and is studied for every busbar in the system. Some researchers put the value of this angle as (0) arbitrarily.
3. Solving the power system balance equations using the latest update of the voltage value and estimator.

4. Use the solution to change the values of voltage magnitudes and angles.
5. Continuously updating both the amounts and the angle of the effort.
6. If the results of the solution are appropriate as specified in advance from stopping conditions, end the simulation and register the results [38].

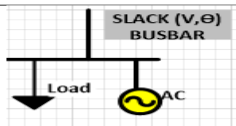
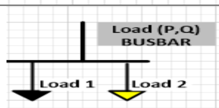
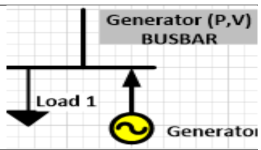
Traditionally, when representing the electrical power system with several elements such as transmission, distribution, loads, there are connection points between these elements that combine them. These points are called bus. Its location indicates one of two things: the first is about generation, injecting power. The second is the load which consumes power.

Moreover, each bus is practically associated in the power systems with four variables that are active and reactive power, voltage magnitude, and voltage phase angle (δ). According to solutions of power flow, the bus is divided into types that can be explained as follows [40,41]:

1. The Slack (Swing) bus: It is a single bus designated to be the magnitude and angle of the voltage specified, it means that the amount of voltage and angle is known. In general, phase angle is zero for most engineers when solving problems. But the value of active power and reactive power is unknown at this point. Choosing it must be a source of active power and reactive power for the circuit or the whole system.
2. Load (P-Q) bus: It is a bus connected to power system in which the active and reactive power is fixed. Sometimes the load bus might include a generator with a specific output of effective and Reactive power. It cannot supply the necessary reactive power support due to limitation of voltage set at a preset value.
3. Generator (P-V) bus: It is the bus in which the voltage's magnitude and the active power is known, so it is called (P-V) bus.

Table 2.1 shows the types of buses and the known and unknown values in them that are required to solve the problems of load flow [39].

Table 2.1. Types of buses and the known and unknown values.

BUS Type	Variables Given (known)	Variables Found (unknown)	SYMPLE
Slack bus	Angle of voltage (Θ)	Real power	
	Magnitude of voltage (V)	Reactive power	
Load bus	Real power	Angle of voltage	
	Reactive power	Magnitude of voltage	
Voltage control, generator bus	Real power	Voltage angle	
	Magnitude of voltage	Reactive power	

2.5.1. Gauss-Seidel Method

It is one of the methods for solving nonlinear equations using the approximation method, and it is considered the simplest to understand the solutions of the convergence logarithms.

To understand the technique of the Gauss-Seidel method, the DC circuit shown in Figure 2.10 will be used.

In power systems, nodes are represented by what is known as Admittance Matrix for various buses, with the help of transmission lines that connect each bus to various other buses. The Admittance Matrix is used to analyze the data that the designer needs from the power system on the buses. It explains the network topology and admittance, the most important features of using network matrix can be mentioned as below:

1. Using the data by bus admittance is very simple.
2. The admittance matrix is easy to reconfigure and modify.
3. The bus entry Admittance matrix is of the sparse type, so it requires less memory in computer [unknown].

Here are the basic rules for creating an admittance array:

1. The diameter of the matrix is the sum of admittance leaving from the bus, also admittance connected to the bus in parallel, plus half the entrance fee specified for every connected line. This is what admittance means.
2. (Y) matrix is a square matrix as the number of nodes and number of diagonal elements in the circuit model are equal.
3. The term (off-diagonal) is symbolized by as (Y_{ij}) takes a negative sign and is the approximation between buses (i) and (j). If the connection between (i) and (j) is not existed, the value of the admittance will be zero.

For the above reasons, the representation of all the values of voltage and current in the electrical network is linked to the next matrix equation.
Since it is not possible to solve nonlinear equations using closed matrix solving techniques, the equations of power flow analysis are solved by what is known as numerical methods that use convergence logarithms [38].

$$[I] = [Y][V] \tag{2.42}$$

Whereas:

$[I]$: Total positive sequence current flow in the buses of network.
$[Y]$: The bus admittance matrix.
$[V]$: Total positive sequence voltage at the network buses.

Due to the physical properties of load and generation, the ends of every node are usually described using a term that defines active power and reactive power as the current in bus is related to these quantities, as follows:

$$I = \left[\frac{P + JQ}{Vi^*}\right] \tag{2.43}$$

Where (*) represents a conjugate for complex quantity and by substituting equation (2.42) into (2.43):

$$\left[\frac{P + JQ}{Vi^*}\right] = [Y]\,[V] \tag{2.44}$$

Figure 2.10. Shows DC circuit which can be used to drive power flow equation method.

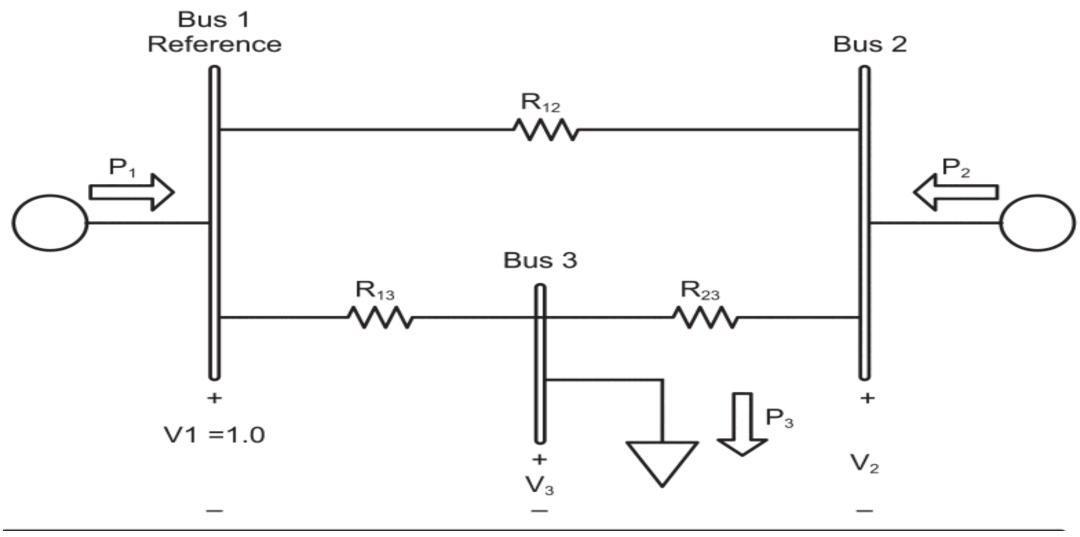


Figure 2.10. DC circuit network of the power system.

1. Bus 3: A load bus is designated for one power per unit.
2. Bus 2: It is considered a generating bus and it is connected to the generator with a specific power.
3. Bus 1: A slack bus is linked to a swing generator with a specified voltage.

Since it is required to find (V_2) and (V_3) values, the power flow at the node is calculated. From the system equations for using the admittance matrix, the equation 2.42 can be extended to include the representation of the form (2.42).

$$[I_1\ I_2\ I_3\ ] = [Y_{11}\ \ Y_{12}\ \ Y_{13}\ Y_{21}\ \ Y_{22}\ \ Y_{23}\ Y_{31}\ \ Y_{32}\ \ Y_{33}\ ] \times [V_1\ V_2\ V_3\ ] \tag{2.45}$$

There is no actual real connection between each pair of buses, so the representation of the matrix in the admittance tends to be scattered.

From Equation (2.42)

$$I_2 = \ Y_{21}\, V_1 + \ Y_{22} V_2 + \ Y_{23}\, V_3 \tag{2.46}$$

Or

$$V_2 = \frac{1}{Y_{22}} \, [I_2 - (\ Y_{21}\, V_1 + \ Y_{23}\, V_3)] \tag{2.47}$$

Where:

$$P = I\ V \tag{2.48}$$

$$I_2 = \frac{P_2}{V_2} \tag{2.49}$$

Substituting (2.46) into (2.47):

$$V_2 = \frac{1}{Y_{22}} \left[\frac{P_2}{V_2} - \ Y_{21}\, V_1 + \ Y_{23}\, V_3)\right] \tag{2.50}$$

And for bus (3):

$$V_3 = \frac{1}{Y_{33}} \left[\frac{-P_3}{V_3} - \ Y_{31}\, V_1 + \ Y_{32}\, V_{32})\right] \tag{2.51}$$

The solving problems for AC in distribution networks are similar to solving DC circuits with extend and replacing resistance instead of impedance, the apparent power (S) replacing active power (P), the result is apparent power equation:

$$S = V\ I^* \tag{2.52}$$

$$I^* = \frac{S}{V} \tag{2.53}$$

And:

$$S = P + jQ \qquad (2.54)$$

Substituting (2.53) into (2.54):

$$I^* = \frac{P + jQ}{V} \qquad (2.55)$$

$$I = \frac{P - jQ}{V^*} \qquad (*) subsitute \ \ in \ (S) \qquad (2.56)$$

For n buses and by taking bus (i) as a reference, and comparing equation (2.42) and (2.52), we get:

$$P_i - jQ_i = \ V^*{}_i \sum_{k=0}^{n} \quad Y_{ij}V_{ij} \qquad (2.57)$$

Also, by rearranging equation (2.57):

$$P_i - jQ_i = \sum_{k=0}^{n} \quad Y_{ij}V_{ij} \, V^*{}_i \qquad (2.58)$$

$$V^*{}_i = \frac{Pi - jQi}{Y_{ii}} \sum_{k=1}^{n} \quad Y_{ij}V_{ij} = \frac{1}{Y_{ii}} \left[\frac{Pi - jQi}{V^*{}_i} - Y_{i1} \ V_1 - Y_{i2} \, V_2 - Y_{in} V_n \right] \qquad (2.59)$$

Which give the final equation for the (N) bus:

$$V_i^{(m)} = \frac{1}{Y_{ii}} \left[\frac{Pi - jQi}{V_i^{*(m-1)}} - \sum_{j=1}^{i-1} \quad Y_{ij}V_{ij}{}^{(m)} - \sum_{j=i+1}^{N} \quad Y_{ij}V_j{}^{(m-1)} \right] \qquad (2.60)$$

N: is the present the number of buses in the system.

m : is present iteration number

i, j : are bus indices

V^* : is the complex conjugate of V

The equations (2.50) and (2.51) are a convenient form for applying the Gauss-Seidel convergence method. Follow the steps below for the problem solution of the Gauss-Seidel iteration:

1. Assigning estimated values to each of (V_2) and (V_3) knowing that the value of (V_1) is constant.
2. Calculate new values for (V_2) from the estimated values for (V_2) and (V_3).
3. Calculate a new value of (V_3) from the initial value of (V_3).
4. Repeat steps (2) and (3) until reaching what is known as the convergence solution.

Voltage calculation is said to be convergent when the calculated voltage and the previous voltage value come close to the accuracy set for each bus in the system[38].

There are several ways in which it determines when the solution converges, and one of the reliable methods is the power mismatch (real and reactive), as the program calculates the total of real and reactive power for whole branches connected to the bus and then compares them with the values set by the user previously specified, and thus the difference which is power mismatch calculates how close the computed voltage is to the ideal value. In general, the power mismatch toleration is determined by a value close to (00001 - 0001) per unit based on (MVA)[37].

Although the power mismatch is more accurate than the voltage convergence, the voltage check is faster like the arithmetic way and digital computing, and a large change in the power mismatch has a small effect on the voltage values, for all of these reasons, avoiding the usage of power mismatch is preferred until the values of the change in voltage appear small [38].

2.5.2. Newton-Raphson Methods

It is used for solving nonlinear equations, including the equations of electrical power systems. The Newton-Raphson method achieves convergence through the use of partial differentials with fewer repetitions than the Gauss-Seidel method with a slightly greater number of computations.

We apply the method of the Newton-Raphson technique on the circuit in Figure 2.10 where the bus power is expressed as non-linear with the voltage function of the same bus.

$$P_1 = V_1(Y_{11}V_1 + Y_{12} V_2 + Y_{13}V_3)$$
$$P_2 = V_2(Y_{21}V_1 + Y_{22} V_2 + Y_{23}V_3) \quad (2.61)$$
$$P_3 = V_3(Y_{31}V_1 + Y_{32} V_2 + Y_{33}V_3)$$

A small alteration in voltage of the bus leads to a small alteration in power of the bus. The linear change between the changes in power can be expressed as the change in the voltage function as following:

$$[\Delta P_1 \; \Delta P_2 \; \Delta P_3] = \left[\frac{\partial P_1}{\partial V_1} \; \frac{\partial P_1}{\partial V_2} \frac{\partial P_1}{\partial V_3} \; \frac{\partial P_2}{\partial V_1} \frac{\partial P_2}{\partial V_2} \frac{\partial P_2}{\partial V_3} \; \frac{\partial P_3}{\partial V_1} \frac{\partial P_3}{\partial V_2} \frac{\partial P_3}{\partial V_3}\right] \times [\Delta V_1 \; \Delta V_2 \; \Delta V_3] \quad (2.62)$$

Can be written as:

$$[\Delta P_i] = [J] \, [\Delta V_i] \quad (2.63)$$

Since (J) represents the Jacobian matrix, this matrix includes a partial derivation of power regarding the voltages for the group of voltages (V_1) (V_2), and (V_3), in other words, it is the derivation of equation (2.62).

In general, by power flow problems, (ΔV_1) = 0, and (ΔP_1) is not included in the explicit calculations. It is possible to reduce the equation (2.62) to become:

$$[\Delta P_2 \; \Delta P_3] = \left[\frac{\partial P_2}{\partial V_2} \frac{\partial P_2}{\partial V_3} \frac{\partial P_3}{\partial V_2} \frac{\partial P_3}{\partial V_3} \right] \times [\Delta V_2 \; \Delta V_3] \quad (2.64)$$

The change in voltage (V_2) and (V_3) are caused by the change in power (P_2) and (P_3) which are obtained by inverting Jacobian matrix and thus:

$$[\Delta V_i] = [J]^{-1}\,[\Delta P_i] \tag{2.65}$$

This method is founded on the following steps to solve problems of power flow:

1. Set an initial value for the voltage (V_2) and (V_3).
2. Find the value of (P_2) and (P_3) from equation 2.61.
3. Calculation of power difference (ΔP) between the calculated value and specific power:

$$[\Delta P_2] = P_2 - P_2{}' \tag{2.66}$$

$$[\Delta P_3] = P_3 - P_3{}' \tag{2.67}$$

The prime sign indicates a specific value.

1. Because the condition ($\Delta P \neq 0$), an error in the voltage will occur. Therefore, the voltage must be incorrect to be close to the approximation (ΔV) that is evaluated from equations (2.66) and (2.67), and for these reasons the voltage for each bus is calculated through a new equation:

$$[V_2\ V_3\ ]_{new} = [V_2\ V_3\ ]_{old} - \ [J]^{-1} \quad [\Delta P_2\ \Delta P_3\ ] \tag{2.68}$$

This equation is the basis of Newton-Raphson convergence method.

2. Recalculating and then inverting the Jacobian matrix by using the latter calculated effort, then calculating a new estimation potential for the voltage using equations (2.66), (2.67), and (2.68). Repeating these steps until (ΔP_2) and (ΔP_3) are less than the specified value for the convergence criterion.

2.5.3. Fast-Decouple Method

In the event of an AC load, Jacobian becomes dedicated in the following form:

$$[\Delta P\ \Delta Q\ ] = [J_1 \qquad J_2\, J_3 \qquad J_4\ ] \times [\Delta V_2\ \Delta V_3\ ] \tag{2.69}$$

Since the voltages here are written in polar ($|V|L\theta$), it is generally possible to rearrange the Jacobian matrix to suit the selected software techniques. It is possible to obtain the convergence of Newton-Raphson method by observation. Any change in the amount of voltage in the bus will result in a little alteration in the real power. By adjusting, any little alteration in the voltage angle in the bus results in a small change in the ineffective power. So, from equation (2.69):

$$[J_2] = \left[\frac{\partial P_3}{\partial |V|}\right] \cong\ 0 \tag{2.70}$$

$$[J_3] = \left[\frac{\partial P_3}{\partial \theta}\right] \cong\ 0 \tag{2.71}$$

Thus, this allows separating equation (2.69) to become as follows:

$$[\Delta P] = [J_1] \times [\Delta \vartheta] \tag{2.72}$$

$$[\Delta Q] = [J_4] \times [\Delta |V|] \tag{2.73}$$

The last two equations may be solved separately from the other equation. This reduces storage and dissolution time when compared to using a complete Jacobin matrix. In general, the Fast-Decouple method is used in applications where the arithmetic velocity time is very important to reach the real solution. It is used in cases of achieving a series of contingency states around a previously solved reference state [38].

2.5.4. Comparison of Load Flow Solution Method

The three methods mentioned before are considered the basis of power flow systems analysis approach. However, it is helpful to know how power flow technologies work but it is also necessary to realize the specifications that those technologies show, as there are many differences between these methods, especially that each method has benefits and drawbacks. Table 2.2 clarifies the characteristics of each technology when and where it is used in an electric power system.

Table 2.2. Comparison between load flow solution techniques

NO	Gauss-Seidel method	Newton-Raphson method	decoupled-Newton-Raphson method
1	Rectangular coordinate based for the solution.	Polar coordinate based for the solution.	Polar coordinate based for the solution.
2	More number of reiterations to achieve acceptable solution.	Less number of reiterations to achieve acceptable solution.	Less number of reiterations to fulfill acceptable solution.
3	The time for each repetition is relatively short due to the small number of mathematical operations.	The time for each repetition is greater (8) times than **Gauss-Seidel Method.**	The time for each repetition is greater (2~3) times than **Gauss-Seidel Method and (5)** times than **Newton-Raphson method.**
4	Number of reiterations is depending on the system's size increment as increasing size system.	Number of iterations is independent on the system's size.	Number of reiterations is independent on the system's size.

PART 3

POWER SYSTEMS LOADS AND QUALITY

3.1. Load Classification and Modeling

In modern electric distribution networks that are connected with distribution generators, the load plays an essential role in energy management, as this energy management view has created new concepts named load response and demand response. Here, a new behavior of loads has been defined.

At the time of the peak network load, some loads can be shifted to a time outside the peak consumption of the loads on the network and conforming to the contract between the costumer and the network holder.

The loads are divided into 3 main parts as illustrated in Figure 3.1 [27]:

1. Consumption.
2. Importance.
3. Responsive.

A) Consumption Load

Refers to three types:

- Domestic.
- Commercial.
- Industrial.

B) Importance Load

In terms of importance, it refers to:

- Critical.
- Non-critical.

Like hospital loads and home loads, successively.

C) Responsive

Responsive loads (RLs) are divided into two types:

- Flexible loads.
- Specific loads.

Response loads contain different types with additional characteristics of response behavior. It is shown to the classifications of loads what is known as unresponsive loads, which is the opposite of response loads, where the load is fixed or uncontrollable, as there is no connection between the supplier and the costumer. Figure 3.1 shows the group of load classifications and the contribution of each type. Recent studies have generally focused on responsive load, the response of which is due to various benefits such as economic benefits as well as increased controllability. Despite the many classifications of loads, a fact that must be mentioned, most of the facilities and loads that are connected to a microgrid as household loads, the reason is due to the applications of the microgrid and the power capacities where the installation is closer to small cities [27].

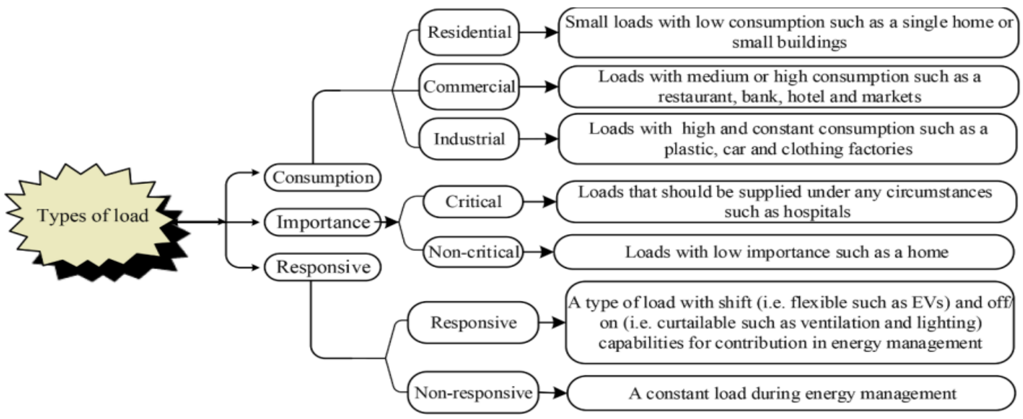


Figure 3.1. Types and classifications of load [27].

3.2. HARMONICS

Electrical power system's harmonics are not a fresh subject, but the widespread use of high power transformers utilized in motor rotation and control has raised the importance of development and research in various fields related to harmonics. High voltage DC terminals have become a focus of the study of harmonics, due to the use of rectifiers and transformers. In recent years, power electronic devices that can handle different power sizes of kilowatts and megawatts have become reliable and commercially available products. Thus, it led to widespread use of transformer usage topology; all these devices represent a non-linear factor in the power system, Figure 3.2 shows distortions of the waveform verses the pure source wave [35,41] .

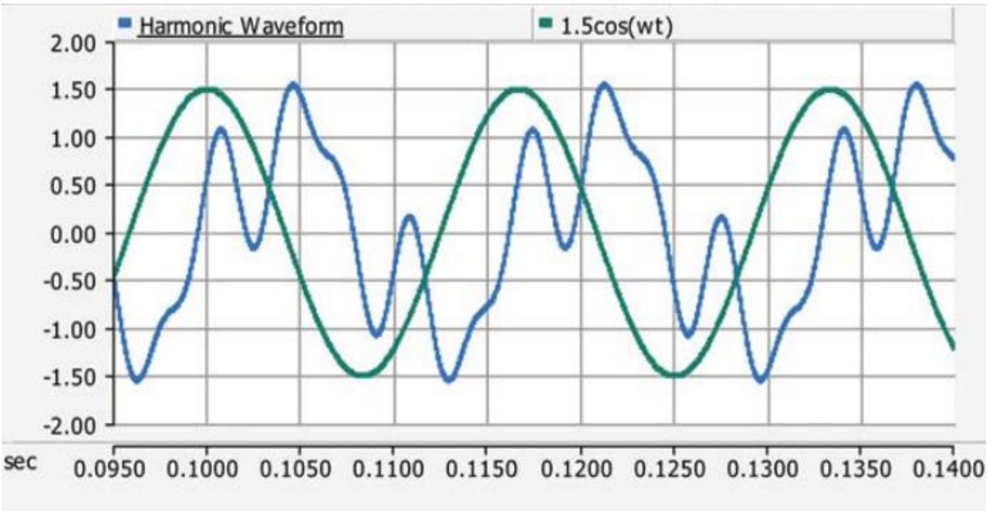


Figure 3.2. Waveform distortions with pure wave source.

Although semiconducting power parts are the main cause of harmonics in a power system, other types represent the elements of nonlinear properties in electrical power systems. More broadly, the load that produces harmonics can be grouped into three categories:

1. Arc loads: Where loads are arched such as arc furnaces and fluorescent lighting.
2. Semiconductor converter: Loads and semiconductor transformer loads as adjustable speed motor control.

3. Iron magnetic saturation loads: Iron magnetic saturation loads cores like overexcited transducers.

Both types (1) and (2) produce harmonics which mostly minimize by decreasing frequency, neglecting the load rates. The same foundations of theories are applied to study energy quality issues related to harmonics. In many instances, any distorted waveform of an electrical power system wave (current, voltage, magnetic flux) can be appeared as a series of DC and an infinite sum of sinusoidal terms, equation 3.1.

$$f(t) = F_0 + \sum_{i=1}^{\infty} (\sqrt{2}F_i\omega_0 t + \theta_i) \quad (3.1)$$

Where:

F_i: Magnitude wave.
θ_i: Phase angle.
ω_0: Fundamental of the power frequency.

It should be noted that not all loads result in multiple integer harmonics of the power frequency. Correct harmonics generally refer to internal harmonics generated by an electric arc or toroid transformers. In general, both integer and integer multiple harmonics are treated analytically in the same way. Usually, it depends on the overlay method.

The basis of wave distortion analysis is the assumption which the waveform is in a steady status. In the practical case, the vector deformation varies greatly and is generally dependent on both the load level as well as the conditions of the power system. It is usual to have a stable moment at the time the measurement is taken, but the next and later measurements may vary greatly.

Both (IEEE) and (IEC) institutions have published determinants of harmonics which are supposed to be applied from a utility point of view to determine acceptable levels of harmonics in the power system, and (IEC) has gone further to publish the harmonics of individual parts of the system.

IEEE covered the determinants of harmonics through two documents. Two methods were proposed through which the harmonics can be defined in the first power system, which is one set of harmonic limits that are the harmonics of current which can be injected at a point in the system of origin named the Point of Common Coupling (PCC).

The second one is set of harmonics determinants for voltage harmonics, which the manufacturer supplies to any consumer. This approach found in the two approaches, makes sure that the consumer cannot inject irresponsible quantities of current harmonics into the system and thus makes sure that the injection of irresponsible quantities of any or all consumers lead to overvoltage distortion. Table 3.1 shows the proposed current harmonic limits for origin consumers and is divided to several columns and rows based on the number of harmonics, short circuit current about load ratio, level of voltage, and total distortion [35].

Table 3.1. Harmonic current limits of IEEE-519 [41].

I_{sh}/IL	$h \leq 11$	$11 \leq h \leq 17$	$17 \leq h \leq 23$	$23 \leq h \leq 35$	$35 \leq h$	TDD
<20	4.0	2.0	1.5	0.6	0.35	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

The basic idea of limiting current harmonics is to allow more consumers who pay more for the power transmission equipment and thus allow injecting as much as current harmonics into the system can absorb without producing an increase in voltage. Moreover, the consumers served at the transmission voltage levels are more restrictive to the injection parameters than the consumers served at lower voltages, and the reason is that the higher voltage network can negatively affect the number of other consumers in voltage distortion.

Table 3.2 illustrates the voltage distortion limits with the same current parameters. Thus, the levels of harmonics are reduced for higher voltages to minimize problems that most users of the system may encounter.

Table 3.2. Voltage harmonic limits of IEEE 519-1992 [42].

Bus voltage at PCC V(L-L)	Individual Harmonic Distortion in %	THDv %
V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
V > 161 kV	1.0	1.5

3.2.1. Harmonic Effects

In general, the presence of harmonics can cause the following problems [42]:

1. Overheat for power transformers and rotating devices.
2. Increased magnetic hysteresis losses.
3. Reducing the apparent power capacity (kVA).
4. Overload related to the neutral line.
5. Voltage and current wave distortion.
6. The failure of the capacitance bank.
7. A trap for the circuit breakers and the fuses.

3.2.2. Harmonic Solution Method

If a consensual study refers to a specific problem like increasing the limit, the solutions are divided into two categories:

1. **Reduce Harmonics**

Reduce harmonics at the point of origin (prior to entering the system), using several methods to connect transformers to remove unwanted harmonics is a previous effective method, but in any case, thinning and reducing the origin point is efficient only in the expansion or design of a source. But for a present facility, the harmonic filter is the least expensive solution.

2. Harmonic Filter

Harmonic filter may be further divided to 2 types [42]:

a) Active Filter: It is considered to be the most economically feasible filter that is produced for high power usage and works as below:

When the load inserts amounts of harmonics to the supplied system, the DC/AC inverter can control the control current as the harmonics inverter device can control the current to load when allow the power system to feed the power frequency of the current to load. Figure 3.3 illustrates the working scheme of the active filter.

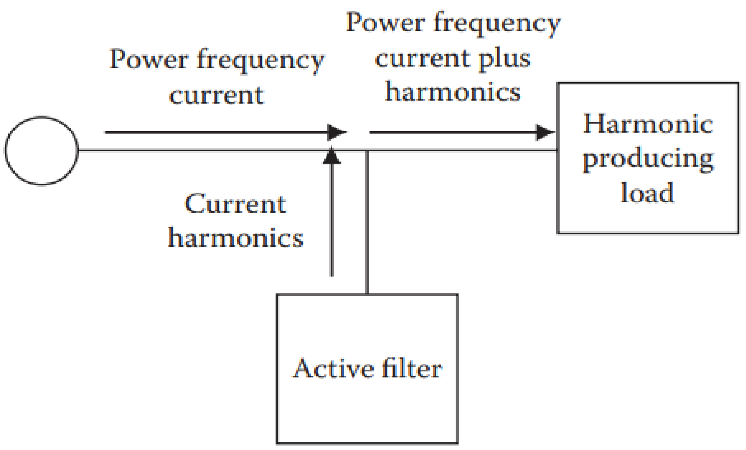


Figure 3.3. Active harmonic filter.

b) Passive Filter: In high power usage or in applications that a capacitive power factor corrector is formerly present, the use of a passive filter is more economically feasible. The negative filter is based on the principle of series resonance, and one of its benefits is that it can be implemented easily. It is often used to filter the fifth or seventh harmonic. Figure 3.4 shows the scheme of the negative filter.

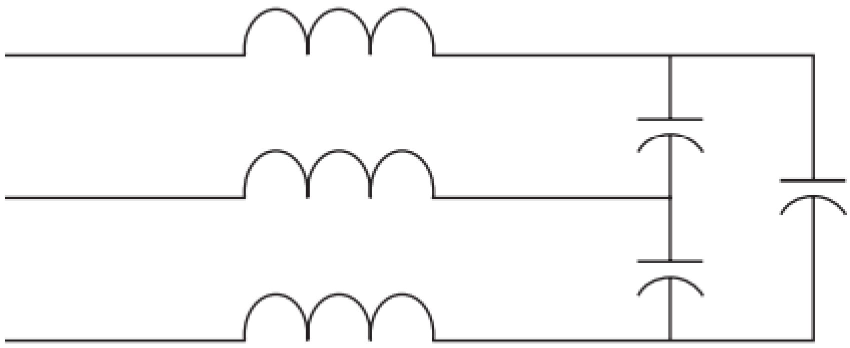


Figure 3.4. Passive harmonic filter.

Fortunately, harmonics measuring equipment is available and ready, and the analytical theories for computer-assisted harmonics assessment are well understood.

3.3. VOLTAGE, FREQUENCY QUALITY AND REGULATION

One of the other issues and effects that are always related to the power quality is called sag voltage. When voltage level drops to less than (0.9) p.u., the voltage's quality will be greatly affected and therefore the electrical system will suffer from sagging, the result will cause faults as well as increase the loads on the system. As an example of this, hot summer days with increased AC loads from consumers usually cause a voltage drop in distribution network feeders. If the current remains within the capacity of the feeder line, this situation can be addressed through the tap changer transformer where the operating voltage bundle in the transformer secondary winding is (126-114 V) and (220-210 V), also any drop below the value of (0.9) is considered as voltage drop (sag) in the secondary distribution. Several reasons may cause a voltage drop, for example, the start of motors may cause a temporary voltage drop. Several methods support the system through the addition of reactive power, a capacitor bank, and a star-var compensator.

There are several practical ways to treat the problem of voltage drop, including the use of (TR transformers), and some of them can be summarized in the solution method [41].

3.3.1. Uninterruptible Power Supply (UPS)

This method depends on the stored energy to support the voltage drop. When voltage sag is detected, the equipment load is shifted from the main source to the UPS. In other words, the load capacity that can be equipped is directly proportional to the amount of stored energy.

3.3.2. Flywheel and Motor-Generator (MG)

The work principle of this system is to store the inertial energy from the stock in the flannel and then use it to compensate for the decay of voltage. The flywheel is accelerated to very high speeds and when a voltage descent occurs, the rotational energy of the flywheel is used to feed the load.

3.3.3. Static Var Compensator (SVC)

The electrical power device is connected in parallel with the feeders. It performs the principle of compensating and injecting reactive power into the loads. Thus, it supports the effort and reduces sagging. Such types of devices may not contain stored energy. The one that contains storage is characterized by the ability to compensate a longer and farther from the voltage [41].

PART 4

DISTRIBUTION GENRATION

4.1. DEFINITION OF DISTRIBUTED GENERATION

Distribution generators (DGs) are given different definitions. The editor Ackermann analyzed these differences in definition and concluded that DG is an electrical energy source that is connected directly to the DN system or the customer part at the energy meter [43].

Because of the wide difference in the definition of distribution generators, he discussed the following issues to give a definition specifically purpose, technology, power delivery area, rating of distributed generation, location, environmental impact, and mode of operation.

The term Distribution Generators always refers to the generation that delivers and connects to distribution networks. DG can be connected directly to a substation or branch network through a power distribution system. Sometimes the small size of distribution generation makes it possible to place it close to the consumer. Typically, generation capacity of the distribution is around 5 MW (IEEE STD 1547). In general, the power distribution system can limit the rated value of the generating units in accordance with the approved policies and design [44].

There are five factors that led to the rapid development of distribution generators that can be summarized as below [45]:

1. Renewed efforts in applying new technologies in distribution generators.
2. Stay away from the restrictions of establishing new transmission lines.
3. The consumer always desires to have a reliable source.

4. Liberalizing the electricity market from governments and giving investors an opportunity.
5. Great encouragement to use green energy.

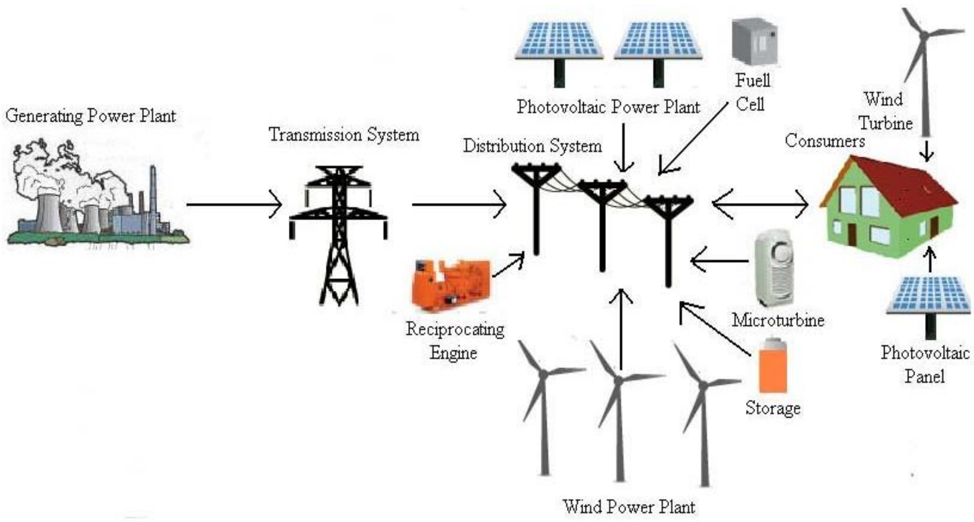


Figure 4.1. Bidirectional DG linked with power system.

Connection DG to the distribution grid system can have benefits for the system itself in terms of voltage support, reduction grid losses, and backup electrical power system. Despite the mentioned benefits, several aspects and techniques have to be taken into consideration when linking generation units to distribution system to give reliability and stability to the system [34].

4.1.2. Distributed Generation Advantages

1. Reducing the losses of the distribution system and transmission lines, and the reason is that distribution generators are generally installed near the customer, thus replacing part of the transmission lines with penetration, and thus reducing the cost resulting from losses.
2. Because the distribution generators contain power electronic equipment, they will consume the returned power, and thus improve the voltage profile, then the result is reduced to regulating equipment such as capacitor and prices of maintenance. It is worth noting that the amount of refinement relies on the location and size of distribution generators.

3. Growth of loads causes increase in demand for energy. Distribution generators can play a role in covering this increase in demand without the need to increase the capacity of the traditional power system as productivity will reduce or delay the need to increase the construction of transmission lines and new distribution networks and modernize the power systems current.
4. Distribution generators are flexible devices in terms of ease of installation as they are located near the consumer center. This possibility allows getting rid of site difficulties such as geographical restrictions in mountainous areas or islands, as they are not restricted by governments to a specific location.
5. The available distribution generators have a wide capacity ranging from 3 kW to 50 MW. This feature has given the ability of distribution generator units to be installed near MV/LV distribution networks.
6. Distribution generators require a short time to be installed and can be assembled easily. Each unit of the distribution generator is not dependent on or affected by the other units, as it can work on its own.
7. Distribution generators are considered environmentally friendly compared to traditional generating stations as they produce electricity with few gas emissions which may reach the value of zero.

It should be noted that as distribution generation has benefits, it has a significant negative effect on the main distribution system because the distribution system was not prepared to carry a domestic generation host and as a result of that limited style, a negative impact will appear as voltage spike, harmonics, island, etc., which will be discussed in the following section [34].

4.1.3. Distributed Generation Disadvantage

It should be noted that distribution generation has a significant negative effect on the main distribution system because it was not created to carry a domestic generation host and as a result of that, negative impact will appear in limited design as [34,36].

1. Continuing to connect distribution generators leads to more complexity of the power system, control, protection, operation, and safety, so it needs a new study and development of new technologies as well.
2. Injection of distribution generators leads to fluctuation and disturbances in the system voltage due to mismatch of synchronization with the main power generators.
3. Although distribution generators reduce power losses, in some cases they increase due to network equipment and technology used for distribution generators.
4. Distribution generators insert harmonics to power system since they are linked to the system through power transformers.

4.2. TECHNOLOGIES OF DISTRIBUTED GENERATION

Distribution generation does not depend on a specific technology reference. Various technologies were used in the management of DG adopted in choosing the primary source of used energy. In recent years, a great effort was made in the use of renewable energy to improve and develop DG technology, where the work was directed to the production of small generators that could be applied as distribution generators.

4.2.1. Solar Power (Photovoltaic)

Solar energy can be produced by using the most famous one which is solar panels that are installed on the roofs of buildings, as these panels convert the solar radiation reached on it into electrical energy without burning processes that emit harmful gas [39,42].

In general, the energy generated by solar panels is proportional to the amount of radiation reach on them, the amount of radiation is referred to irradiation or insolation, this radiation relies on various factors like location, clarity of sky, angle between panels and direction of fall of solar radiation with direct fall of solar radiation and a clear sky from clouds. The amount of radiation is estimated at 1000 W/m, where the highest percentage of the injection capacity produced from the photovoltaic needs is

captured by what is known as Maximum Power Point Tracker (MPPT) logarithms implemented through the inverter that is an electronic device which converts DC to AC to inject the energy generated from the solar cell system into the main grid.
The two PV sets are interconnected into the main grid [39,42].

1- **Stand-Alone**: This type of solar power generation system is completely isolated from the grid's distribution and main network. Figure 4.2 shows most of the contents of this type of Photovoltaic System Generation, the figure actually describes one of the most complex systems and also includes the basic elements in the case of household loads or industrial applications. The contents' number of this system depends on the load's type. It is potential to replace the inverter with a DC-DC converter if the load is (DC), and it is also possible to connect the photovoltaic arrays directly to the load if the operating schedule is not important.

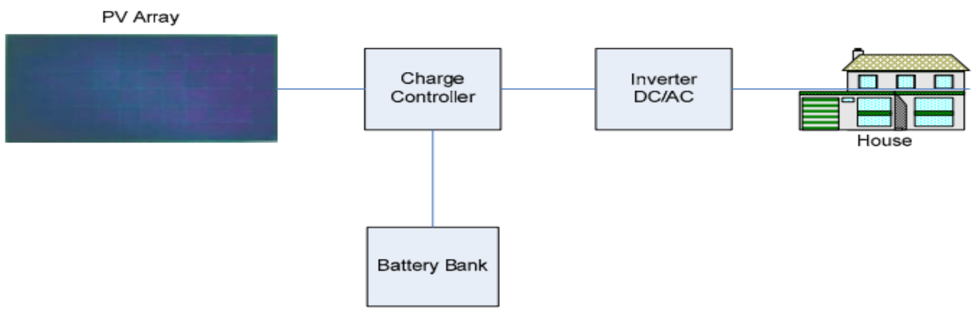


Figure 4.2. Stand-alone PV interconnection.

2- **Grid-Tied (On-Grid)**: This type is directly coupled with distribution networks and main network. In general, it does not require batteries. The operation of this type requires a DC-AC inverter. This type has many advantages over the other type that can be summarized as follows[46]:
   - A small PV array that can supply the same reliable load.
   - Less need for system contents and maintenance.
   - Efficient use of available energy as it contributes to generating the main network while consumer demand is less than the output capacity of the photovoltaic array.

Hybrid system where storage units or diesel generator or both can be combined and linked to main grid in the case of additional reliability and scheduling operating flexibility which means some additional cost. Most industrial companies for home uses use a flat solar cell model because it is available and easy to install. Figure 4.3 shows the on-grid PV system [47,48].

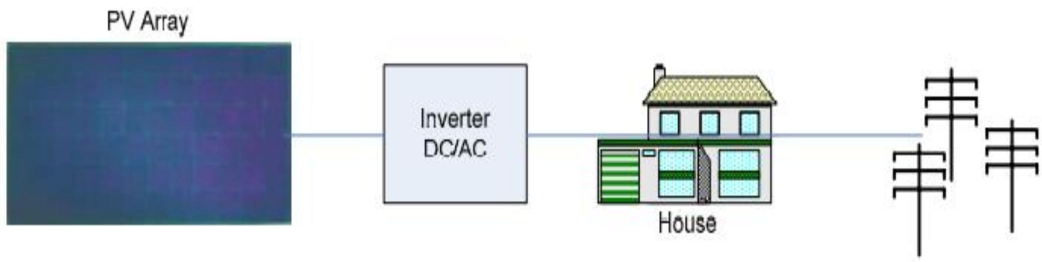


Figure 4.3. Grid- on PV interconnection.

4.2.2. Wind Power

Wind makes kinetic energy and wind turbine converts it to mechanical energy, that is transferred to the generator, where it converts mechanical energy into electrical energy.

Modern wind generators include 3 main elements:

1. The tower, as wind turbine is installed on it.
2. Rotary part and rotor blade.
3. Nacelle that takes the contents of the capsule form, containing the generator and the auxiliary parts.

The generating capacity of wind turbine depends mainly on the speed of wind as well as the space wrapped by turbine blade.

Kinetic energy from the horizontal displacement of the air can be converted into rotational kinetic energy through several blades tied to the wind turbine axis. Then, this it is converted into electrical energy through an electric rotating generator [42].

As wind energy is considered the most feasible when comparing it with different renewable energy resources, wind turbines do not produce any emissions. Wind turbines come in different configurations which are vertical and horizontal and have a diversity of sizes and implementation classified according to the usage or individual scale, as the large scale utility ranges from 1.5 to 5 MW[39]. A basic part of the wind turbine system is illustrated in Figure 4.4.

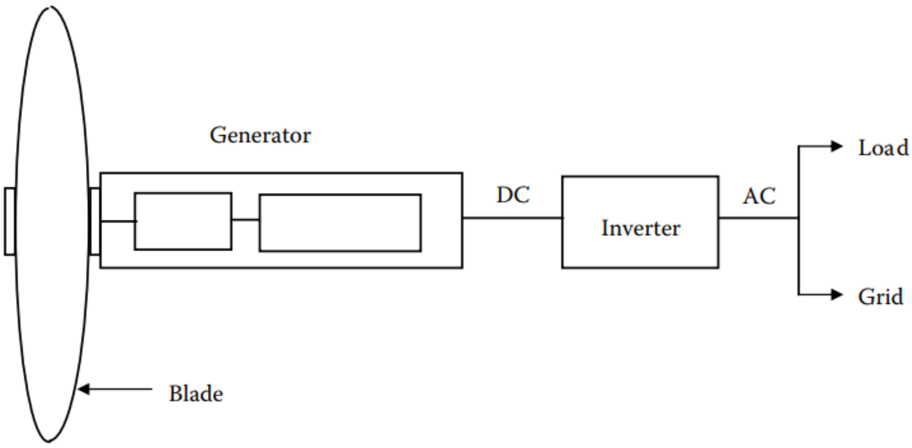


Figure 4.4. Basic parts of wind turbine system.

Prediction wind speed is difficult, and this is reflected in the production of electricity from the wind generator. Forecast accuracy is also important for wind power turbines to take a part in the electricity market and networking. Wind turbine power output is highly dependent on location. In addition, the selection of wind turbines is mainly determined by their location based on wind conditions and not necessarily on proper grid placement[39,49].

There are many technology efforts used in wind power turbines, mainly divided into:

1. Fixed wind speed turbine: It depends on controlling the output power by active power by regulating the angle change of the blade. Therefore, the induction generator consumes reactive power, and for this reason, the capacitance bank is used to compensate the decrease in the consumption of reactive power.
2. Variable wind speed turbine: It is considered more complex than the first fixed speed. The principal goal of it is to acquire the maximum efficiency of aerodynamic air over a wide domain of wind speeds. To get to this, the air

turbine is constantly adapting its rotational speed (w_r) where the tip speed (λ) remains constant through a predetermined value that matches the maximum value of power coefficient. Whereas a fixed speed turbine uses capacitors to compensate for reactive power, a variable speed turbine controls the reactive power to keep it close to zero. In other words, it operates at a unity power factor.

The wind speed turbine generator system consists of:

1. A Double-Fed Induction Generator (DFIG): This type includes a wind turbine with tilt angle control of the blade as well as an induction generator that is linked directly to the main grid and the rotor is driven by a power converter. The turbine is linked to alternator with a gear shaft. The transformer power system can change the wind turbine's speed by controlling frequency of electric power system and the mechanical rotor frequency.
2. A Generator with a Front-End Converter (GFEC): Including a gearless vane step angle control with a multi-pole synchronous generator. The change in the speed of this generator results in a change in the frequency of the synchronous generator terminals, so it is not directly linked to the main network and is connected through what is known as back-to-back converter, the power converter tries to regulate this change by frequency [39].

Mathematical representation of the power wind turbine expresses given by:

$$P = \frac{1}{2}\rho\pi R^2 v^3\, C_P \tag{4.1}$$

Were:

ρ: Air density.
R: Turbine radius.
v: Speed.
C_P: Turbine power coefficient.
Ratio of tip speed (γ) of machine turbine blades to wind speed as:

$$\lambda = \frac{R\Omega}{v} \tag{4.2}$$

Ω: Wind speed.

Where (C_P) is maximum at $(\lambda_{optimal})$.

4.2.3. Fuel Cells

Fuel cells are defined as an electrochemical engine that does not contain a rotating part as it collects the energy released by mixing hydrogen and oxygen. The reaction leads to the generation of electricity, heat, and water while there are no harmful emissions from this process. In principle, it works like all batteries but without the need for decomposition and recharging. The fuel cells still produce electricity while the fuel is available, and the hydrogen needed by the reaction is generated from somewhat hydrogen-rich fuels like propane, natural gas, and methane.

Fuel cells are clean and quiet energies and are considered an on-site generator that converts fuel into electrical energy by an electrochemical process, besides generating electricity, it produces fuel cells that can act as a source of thermal energy, water, and heating surfaces to absorb cooling [42].

Fuel cell cells can operate using natural gas, hydrogen, methanol, etc. The efficiency of fuel cells in producing electricity is up to 65%.

The fuel cell process uses a basic principle. All fuel cells consist of 2 electrodes that are a cathode and an anode, divided by liquid conducting electrons. Through hydrogen stimulation, the atom separates into an electron and a proton, carrying a negative charge and positive charge respectively. The result is the passing of a DC electric current between the poles, and then it is possible to use an inverter to easily convert it into an alternating current. The combination of oxygen and hydrogen at cathode electrode results in heat and water. The fuel cell topology is defined as a storage tank for electrolytic electrodes. Figure 4.5 illustrates the scheme of fuel cell system.

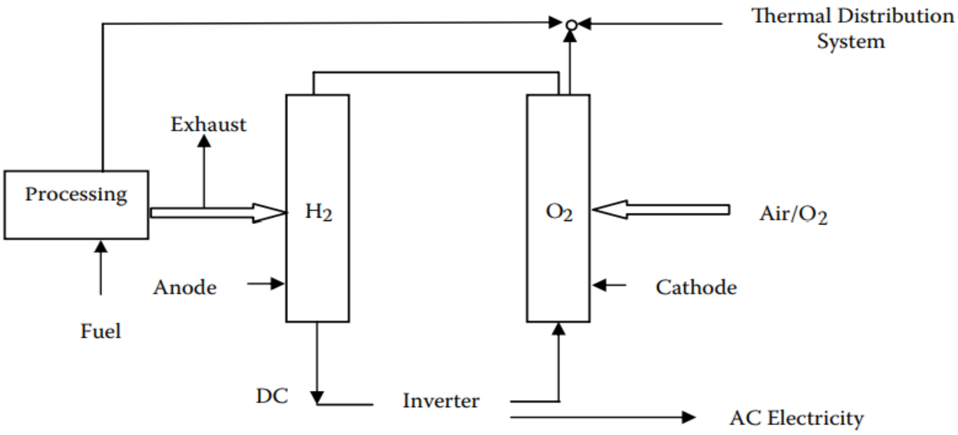


Figure 4.5. Fuel cell systems.

The energies of fuel cell have a small impact on the environment, as well as the lack of maintenance due to the absence of moving parts. However, their performance is considered weak at peak power due to the very high cost [42].

4.2.4. Micro-Turbines

A micro-turbine as shown in Figure 4.6 is a new generation of gas turbine and has smaller size, generating about 25-500 kW. Its working principle is obtained from the auxiliary power system utilized in the aircraft system, diesel motors, and turbochargers. It can work on liquid fuels and gaseous fuels.

Micro-turbine includes combustion chamber, compressor, generator, and turbine.

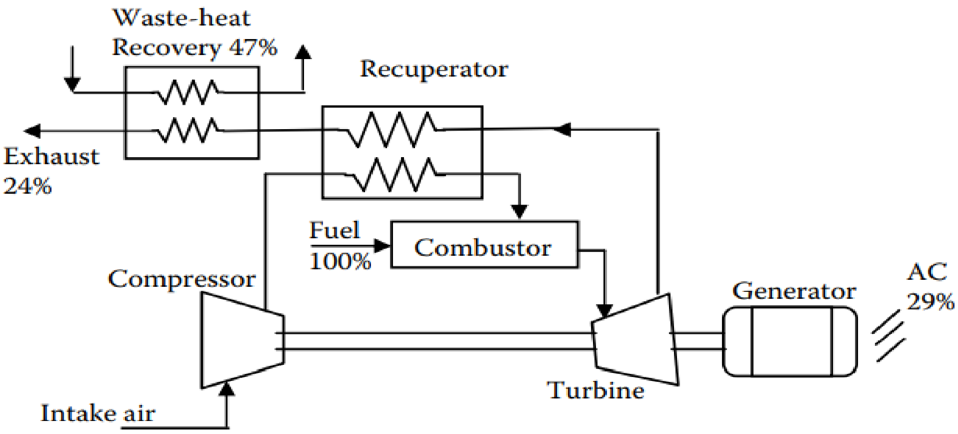


Figure 4.6. Micro-turbine parts.

The air entering the system is compressed by three times of atmospheric pressure and then goes to the heat exchangers which are called Recuperator. The exchanger increases the air temperature from the exhaust gases, the fuel mixes with the heated steam then burns with sufficient energy to run the turbine that will rotate electric generator. Turbine's speed is up to 96,000 rpm and relies on burned air only during its operation. This feature does not require lubrication, which leads to reducing maintenance and operation costs.

The efficiency of micro-turbine is 30 to 40% with a non-recuperator and it reaches 20 to 30% with recuperator. The efficiency of electricity production can reach up to 60% when it is mixed with fuel cell units. Micro-turbine emissions are comparable to large unit turbines. Emission quantities of $(CO_{\times})$ and (CO_2) are field tested by manufacturers. Generally, it's suitable for Combined Heat and Power (CHP) applications. The issue of operating a micro-turbine is its efficiency decreases by increasing temperature, leading to an increase in (CO_2) emission [42].

4.2.5. Stirling Engines

It is renowned as external combustion engine, where its work depends on the cooling and heating of gas through a closed chamber with a piston. Once gas is heated, the gas will expand inside the combustion chamber and generate pressure inside the combustion chamber in turn, pushing the piston out when the gas is cooled. The contraction occurs and then the piston is pulled in. The advantages of Stirling Engine are its rotation is cleaner and more efficient than conventional internal combustion engines [42].

4.2.6. Hydropower

Hydropower is the oldest type of renewable energy source that was used to generate electricity. Most of the visible plants are based on large dams to store water, in general, the level difference between the level up-stream and the down-stream allows the use of the potential energy in the water to rotate the hydro turbine, then the hydraulic turbine converts the head of water energy stored in the dams into electrical energy through an electric generator and then connect to the grid. Hydropower stations are different in size from some MW to hundreds of MW and may reach large installations as well, but they always need a strong transmission system because their installation is far from the customer [39,42].

The power extracted from the water head is given by:

$$P_{EXT.} = H\ Q \tag{4.3}$$

Where:

$P_{EXT.}$: Discharge water.
H: Head water.

4.2.7. Tidal Power

The phenomenon of tides occurs because of the attraction between the moon and the earth which leads to large and high waves in the sea and oceans that can be used to generate electricity. The strength and height of the tides change during seasons and one month due to the moon's rotation around the earth. Despite the large fluctuations in the strength of tidal waves, they are highly predictable.

Tidal wave power is generated by the flow of water between the high wave and the low wave, where the water is trapped at high tidal waves and then allowed to descend in the opposite direction when the tide level is low in the sea. Water flow and tidal force lead to the rotation of the tidal turbine, which in turn is linked to the electric generator and after that to main network. There are several halves of the tidal turbines as in the wind, both horizontal and vertical. It is considered one of the latest types of renewable energy that does not produce emissions, it can be highly predictable, but it is very expensive compared to other renewable energy sources and it needs specific locations where the tidal waves are high, making it specific to use [50,51].

4.2.8. Geothermal Power

It is one of the renewable sources of energy that is extracted from the core or the earth's crust, or by injecting water flow and heating it using dry rock heating technology, where this energy can be converted by mechanical means such as steam turbines in a thermal power plant or by using heat directly.

The center of the Earth contains huge amounts of energy, but only in specific locations, especially islands at present, this location can be used practically to extract energy. Moreover, these locations can naturally produce steam and then be easily used. The production of some geothermal stations has decreased significantly over time as the earth's core heat cannot keep up with the rate of geothermal heat consumption [52].

4.3. DISTRIBUTION GENERATION AND LOSS REDUCTION

The distribution generation operates depending to its part in electrical power system where DG plays 2 distinct roles:

1. A backup source works in case of emergency with a microgrid.
2. Works in parallel with main DN.

In general, the consumer demands a continuous, reliable, and uninterrupted supply of the main service. In other words, the presence of DG can contribute to the case of what is known as the island, where it can give a reliable supply of the required loads through its participation in micro-grid. Microgrid is known as a small-scale power supply system that is able to balance the supply and load required by the consumer to achieve stable service within the boundaries of a specific area [53].

By operating DG in parallel with DNs, it is possible to compensate the exhaustion of distribution and transmission system besides minimize voltage drops and losses.

DG helps in reducing losses as an on-site generator supplies the demand required by loads, more than stations and very large generating units, where energy is drained during long-distance transportation and then to the consumer point. Reducing losses is achieved through factors that are the rate of power supplied from DG and its location [53].

The optimum distribution that ensures reducing losses in the distribution networks according to this study is the ratio of the contribution of the distribution generation to inject an active power ratio (3/2) of the required load, and it is also located at a distance of (2/3) from the total length of the feeder. It is recognized as the rule of (2/3) [34].

Although the application of the rule (2/3) is limited, the model is not real. The distribution generator and the loads are considered as a constant current source, this method is used to demonstrate the effectiveness of reducing losses through the use of DG. Figure 4.7 shows reduce losses with and without DG whereas:

I_i: Load current.

I_{dg}: Current inserted by the DG.

X: The range from feeder to the DG location site.

Now the effect of the current in the presence of DG became clear, as the losses are reduced by reducing the feeder current between the source point and the site of DG. The same behavior can be found in the rest of the electrical systems, despite the more complexity. It is not easy to explain the effect of DG on power system, but this simple example was given to see the extent of the impact of the latter on electrical power system [34].

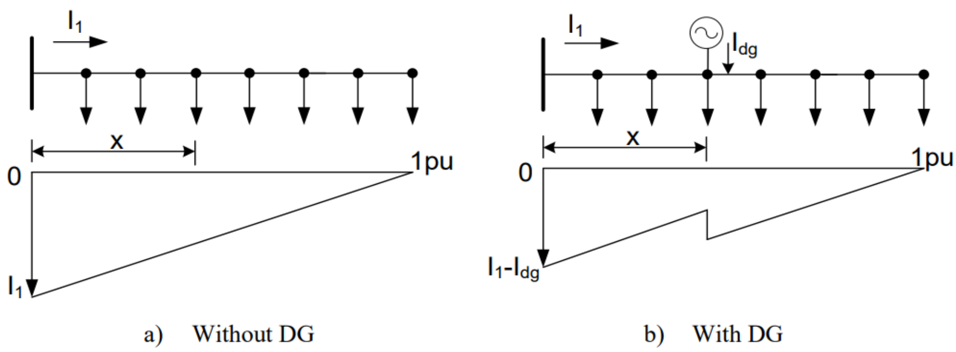


Figure 4.7. Reducing losses on the distribution network.

4.4. IMPACT OF DISTRIBUTED ENERGY RESOURCES ON DISTRIBUTION NETWORK OF POWER SYSTEMS

If DG has great benefits as it is environmentally friendly and saves energy, there is a disadvantage to this type when it is penetrated into the distribution network, as the increased participation of DG system and its penetration into the main network has many disadvantages [54].

4.4.1. Voltage Profile

It is assumed that the distribution generators improve and support the voltage of the power system but the question is how accurate is this statement, since the increased penetration of the distribution generators may cause an raise or reduction in the system voltage , moreover, the distribution generators differ in their technology level output power by varying time as in wind and photovoltaic, and as an inevitable consequence of this, voltage fluctuations occur, which in turn lead to a deterioration in quality of the power transmitted to consumers [36].

In addition, voltage increases or decreases in DNs with distribution generators have been mentioned owing to the incompatibility of distribution generators with current voltage regulation techniques.

Generally, the DNs were organized through voltage regulators; capacitor and tap changer transformer, including the methods designed for the power flow in one direction as it has proven its efficiency in voltage regulation long ago.Nevertheless, at present, distribution generators' installation with power grids had a great effect on methods of power regulation caused by power flow which is bidirectional.

In other words, the distribution generators had a positive effect on the distribution networks through their contribution to controlling reactive voltage compensation, regulating frequency, and working on reverse spinning in the case of a fault indication in main system [36].

4.4.2. Regulation and Balancing

The great integration of renewable energy resources in form of distribution generators from a specialist point of view relies mainly on 2 issues. The first one is the connected grid issue which takes into account the strengthening of network and deals with issues of feasibility and economy. The second one is power system regulation that is related to complex balancing issues. It is not possible to address balancing issues without coordination between all power systems on the local and international level [36].

4.4.3. Power Quality Issue (Harmonics)

Inverter is the core of photovoltaic system generation with grid connection. It oversees the quality of injected power to network. Also, it produces harmonics to the system in the appearance of non-linear loads. Through the transformation process from DC to AC, current harmonics lead to a drop in voltage and thus a voltage distortion in the system. The harmonics also lead to a resonance state in the equipped system, malfunction, reducing in the lifetime, and perhaps permanent damage to the electrical equipment [54].

4.4.4. Increased Reactive Power

Inverters associated with the photovoltaic generation system usually prefer to work with a unity power factor. Also, users of small household generating units have measured power in kWh and are not based on kVA. This is a return to the fact that the inverter in photovoltaic system works at unity as a power factor and the maximum active power. In this case reactive power generated by PV for the required load is at a minimum value. Therefore, the network in this type of connection is in charge of supplying most of the reactive power. This causes distribution networks and power transformers to run at a low power factor [55].

4.4.5. Islanding Detection

The case of insulating detection occurs when photovoltaic generation system keeps feeding the load with electricity although the network supplied from the stations is not present. This case is named insulating detection. Insulating may cause danger to power plant workers, especially in the field of maintenance and repair, who do not realize that the circuit is still active. Therefore, in this case, the inverter circuit must isolate the solar power generation system from the grid quickly in the case of a network malfunction. This function is a PV system known as Anti-insulating [54].

It is found to say that the effect also depends on factors including the system's size and the PV System's location. According to the American Solar Board of Codes, PV System is classified into three main classifications based on the rating according to Table 4.1 as shown below [56]

Table 4.1. Classify rated scale of PV.

Small Scale	Medium Scale	Large Scale
Rated 10 kW or less 	From 10 kW to 500 kW 	Above 500 Kw 

PART 5

IRAQ POWER SYSTEM AND POTENTIAL RENEWABLE ENERGY

5.1. HISTORY OF IRAQ'S ELECTRICITY GRID SECTOR

The history of electricity goes back to ancient decades, as the first electricity connection in Iraq was in Baghdad in 1917, where several streets were lit in Baghdad, and the capacity was a DC. At that time beneficiaries of it might barely surpass a few hundred limited customers. In 1987, the Baghdad Electricity Distribution Company was linked to Iraqi Ministry of Industry. During the first Gulf War in 1990, more than 90% of Iraqi power system plants and generating stations were destroyed [57]. Between 1990-2003, Iraq was subjected to economic sanctions that affected the improvement and production of electricity. In 1999 an Electricity Distribution Company was established by the Ministry of Industry with a capacity of 4,500 MW. In 2003, the ministry of electricity was founded. Between 2003-2007 there were unclear policies, unstable situation, overloading, and unreliable power system, also, gas flaring this has led to the deterioration of power system in Iraq. In 2011, the system only covered 55% of the demand's needs, because of the unreliable grid that pushes the consumer to use private generators to compensate for the outage hours from the main grid. After 2012, the dependence of electricity production on gas has increased. The reliance of power plants on gas to reach 55% of total electricity production has forced Iraq to import gas, even though 60% of the gas that Iraq produces is burned, according to the International Energy Agency (IEA), there is no clear policy to benefit from the gas produced in the previous years. In 2018, the peak grid supply was 16.4 GW, whilst demand peak at 27.3 GW according to IEA in 2019.

5.2. IRAQ'S POWER GRID SECTOR

5.2.1. Electricity Generation

It is significant to know the power system's reliability in any country does not depend on the amount of generation and the capacity of the installed stations, but rather it must take into account several factors like transmission lines, distribution networks, growth demand load, etc. The generation system in Iraq depends on three types of plants: gas turbines, thermal power plants, and hydroelectric plants, while the contribution rate of hydropower stations does not exceed 3% of the total generation in Iraq. Figure 5.1 shows the contribution of plants generation capacity to the national grid [58].

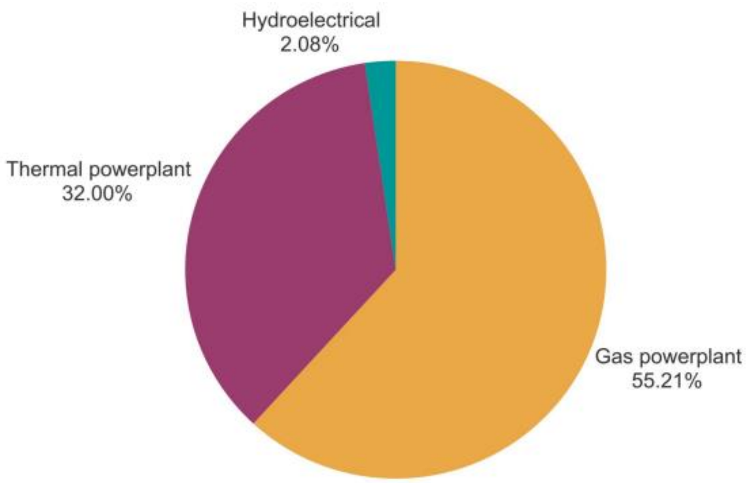


Figure 5.1. Contribution of power plants' capacity according to report of MOE [58].

In 2010, the international generation grid prepared 42% of the required demand load, in 2013 it jumped to 52%, and in 2014 it decreased to 38% due to the war on ISIS, it rose again in 2015 to 57%, whereas in 2019 it reached 70% and in 2020 it became 70.5% of the demand load as illustrated in Figure 5.2 [58].

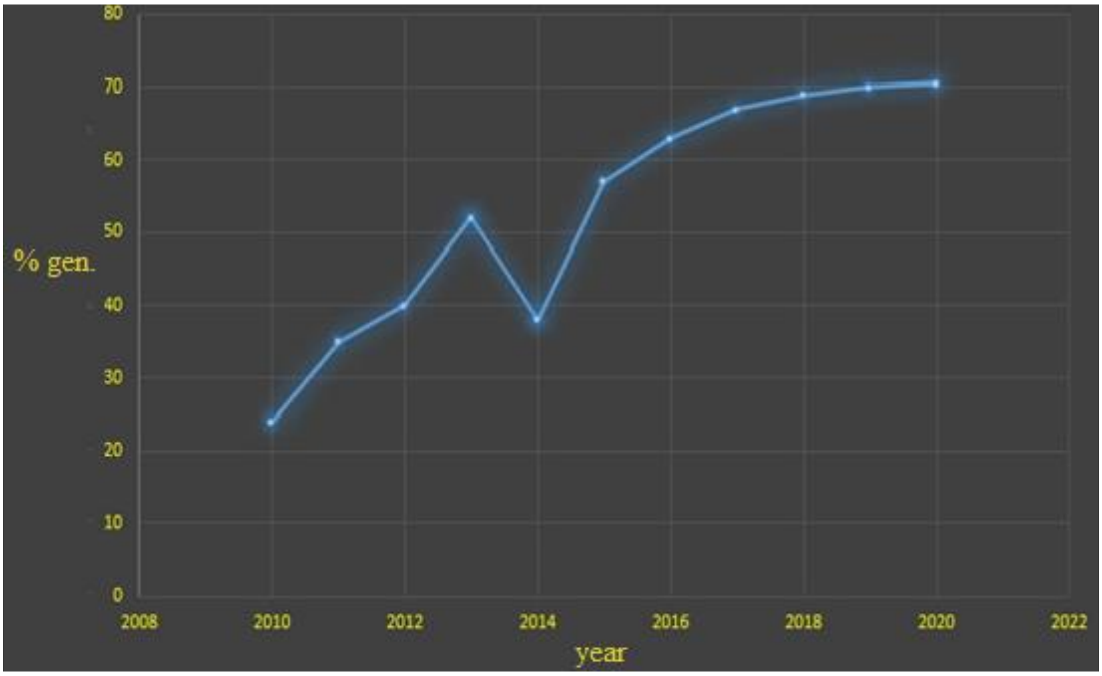


Figure 5.2. The percentage generation capacity to the demand load (2010-2020).

The peak generation capacity in Iraq has reached 19.3 GW, with a load demand of approximately 27.5 GW, despite the installed stations and generation capacity in Iraq are approximately 33 GW, however, the grid needs reliable transmission lines, reduce losses, and reconstruction distribution stations. Therefore, the power outage reached (16) hours per day in the summer of 2020 [59].

In keeping with the International Energy Agency (IEA), the cost of energy from thermal stations is much lower than gas stations, besides that the efficiency of thermal stations is more efficient than gas stations, especially when importing natural gas to the power plant. It is subject to political and economic factors, which stop the export of gas that has a great impact on gas power plants, thus reducing the amount of generation and supply of electricity to the consume [59].

5.2.2. Import Electricity from Neighboring Countries

To compensate shortage of electricity, Iraq relied on the policy of importing electricity from neighboring countries as follow:

1. The Iraq-Iran interconnection is now provided to import electricity from Iran through three main lines divided into 400 kV and 132 kV.
2. Iraq signed an interconnection agreement with Turkey to supply electricity between Mosul, Cizre cities, and Zakho, Silopi, but its operation is on hold.
3. In 2019, Iraq signed an agreement to supply electricity from the Gulf Cooperation Council (GCCIA) countries and build transmission lines to connect Iraq to the Gulf country's system through the Al-Faw city.
4. Iraq signed an interconnection agreement with Jordan to construct technical requirements.

These connections have great benefits by increasing the capacity of national capacity system and increasing it without the need to add or build new power stations, and this has the benefit of reducing the period to increase the capacity of public sector, as well as reducing construction costs and reducing the emissions of gases resulting from the combustion of traditional fuels, in addition to the event of emergency or emergency stoppage at power plants, it is possible to continue supplying electricity through these connections with close countries [58].

5.2.3. Use of Private Generators to Compensate Electricity

The high summer temperature in Iraq, which may exceed 49^{o}C, leads to an increase in the electricity demand. Figure 5.3 presents the gap between supply and generation from the main sector, and power outages occur for up to 16 hours a day. Prompting consumers to use private diesel generators in the neighborhoods to meet their electricity needs. The price of an ampere in Iraq for 12 hours is estimated at 12,000 IQD. The electricity is supplied at a rate of half or three-quarters of the day and the tariff of a private generator is around 125 IQD per kWh. The cost of a subscription will be much more than the price of national grid if a household needs two air conditioners as well as a refrigerator and light, according to the International Energy Agency (IEA). 24 hours may reach 15 USD/amp per month that people must pay approximately 250 USD. The budget for using private generators or neighborhood generators is about four billion $US in 2018, this amount is equivalent to the budget assigned to electricity section in federal budget for capital expenditures for the year 2019 according to the International Energy Agency (IEA)[58].

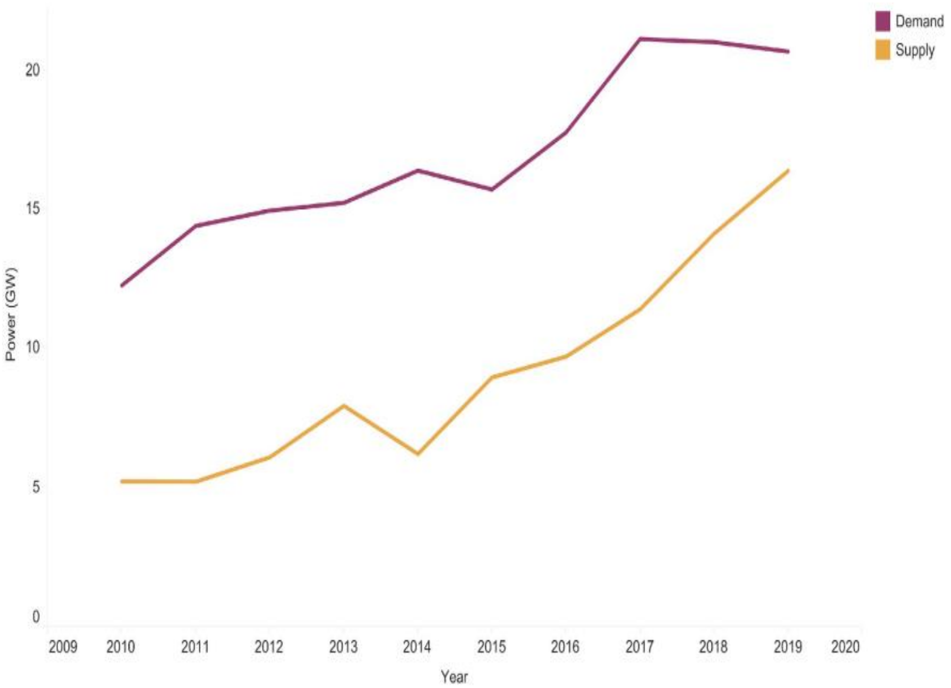


Figure 5.3. Supply and demand load from main grid (IEA) [58] .

5.2.4. Electricity Distribution

Distribution networks in Iraq suffer from several issues, most of which are caused by those who illegally bypass the national network, weak design of the power system, and inefficient distribution networks, in addition to what has been subjected to sabotage and destruction due to the liberation operations against terrorism between 2014-2019. Figure 5.4 shows the crisis of ISIS that has inflicted huge damages to electricity network, evaluated at 7 billion $US, 8 power plants were destroyed while 25 were damaged, 23 substations were destroyed while 63 were damaged, 137 distribution substations were damaged and 47 were destroyed.

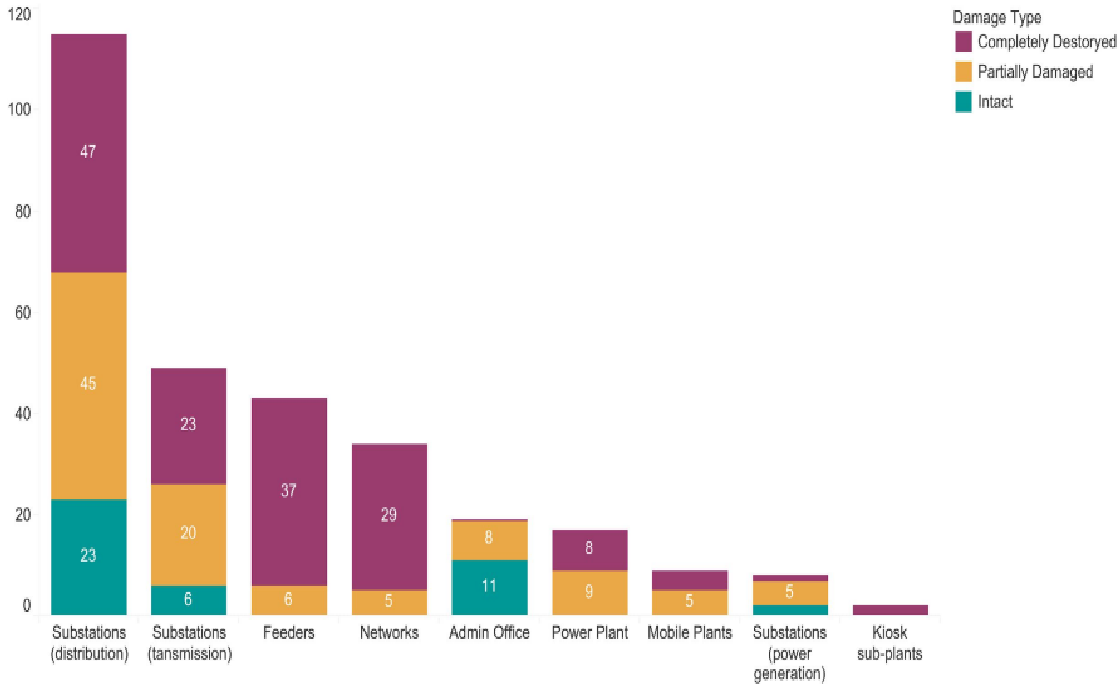


Figure 5.4. Damage assets in conflict-effected area

In keeping with International Energy Agency's report, the losses of distribution networks are a major problem in the power system in Iraq, where the rate of losses reached 54% of the total electricity supply between 2008 - 2019, meaning that only 46% of the supply is obtained by customers and subscribers, Figure 5.5 shows the percentage of losses in the cities of Iraq [58].

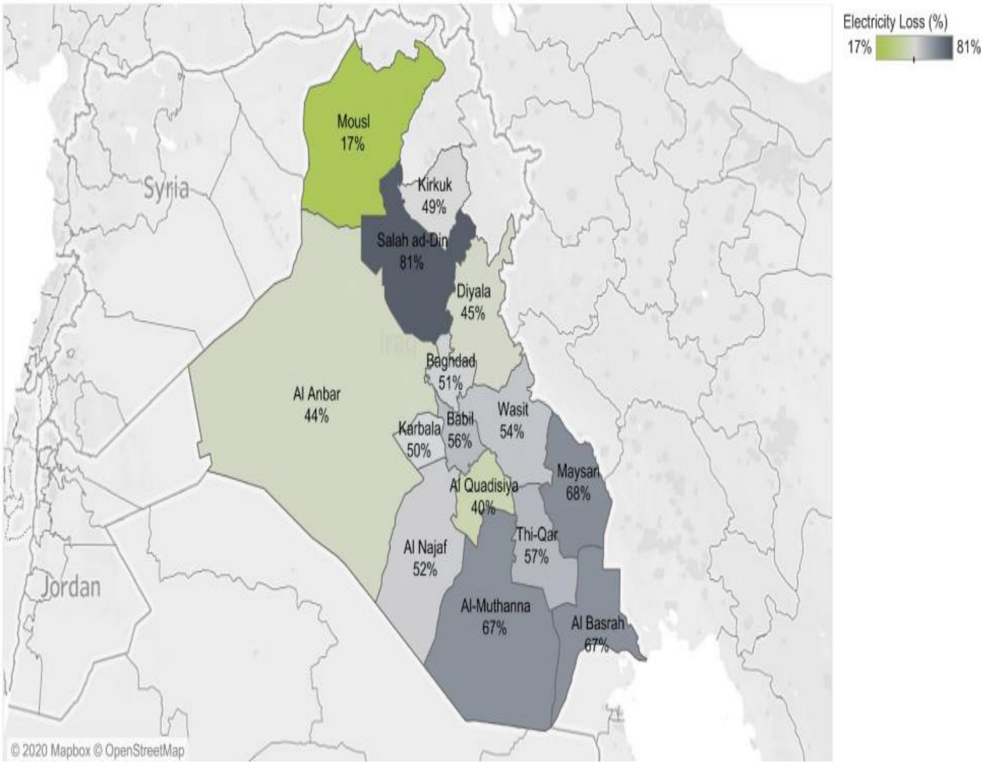


Figure 5.5. Electric grid losses in Iraq cities.

The distribution networks, their value, and the capacity of the loads are very important in the power system. The design must be higher than the required load. In 2017, the number of distribution networks was 812 from 33/11 kV with a full capacity of 36,152 MVA, according to Iraqi Ministry of Electricity in the report's year. The annual capacity of (33/11) kV was 37,859.5 MVA and in low voltage stations (11/0.4) kV. In 2019, the number of secondary stations decreased by 743 with an increase of capacity estimated at 36,456 MVA by adding 114 sub-stations that have 2,180 MVA capacity. Although there are plans to develop distribution networks and adds different capacities, the problem of network trespassers and thieves remains. In 2016, the government in Iraq began granting collection and billing contracts through private sector companies, where their duties are summed up in protecting networks from intruders. These companies faced great challenges in the face of the staff apathy, as well as the lack of experience in managing this field.

5.2.5 Cost and Subsidy

The present amount of electricity financial support ranges from 78.30% to 87.00% based upon 61% of the whole technical and commercial losses as illustrated in Table 5.1.

Table 5.1. Financial support with and without fuel support (2018)

	With subsidized fuel	Without subsidized fuel
Total real generation without commercial losses (million MWh)	102.530	
Total price of electricity generation (billion IQD) [billion $US]	7,2180 [6.04]	12,0320 [10.07]
Losses (%)	61%	
Electricity delivered after commercial losses (million MWh)	39.950	
Collected gain (billion IQD) [billion $US]	1,5680 [1.31]	
Financial support (billion IQD) [billion $US]	5,6500 [4.73]	10,4640 [8.76]
Financial support percentage (%)	78.3%	87.0%

5.3. CHALLENGE AGAINST IMPROVE IRAQI POWER GRID

5.3.1. Trespassing on the Electrical Main Grid

One of the great difficulties facing developing power sector in Iraq is the trespassing of national grid, where there are consumers that use electricity from the national grid without using a meter or paying bills for MOE, as well as the use of uneconomical electrical devices. These factors have led to losses in the national sector of up to 54%, which means that only 46% are partners or install electricity meters, in addition to this, all 46% do not pay bills even though electricity bills are subsidized by the state. Costing the state budget 12 billion USD. Therefore, the use of PPP private companies is important, but it requires more time and training in this field.

In addition to these problems, some users tamper with the internal distribution panels of the houses, which in turn leads to an imbalance in the loads and damage to the distribution network. Figure 5.6 shows the losses in Iraq's sector grid and other countries of the world.

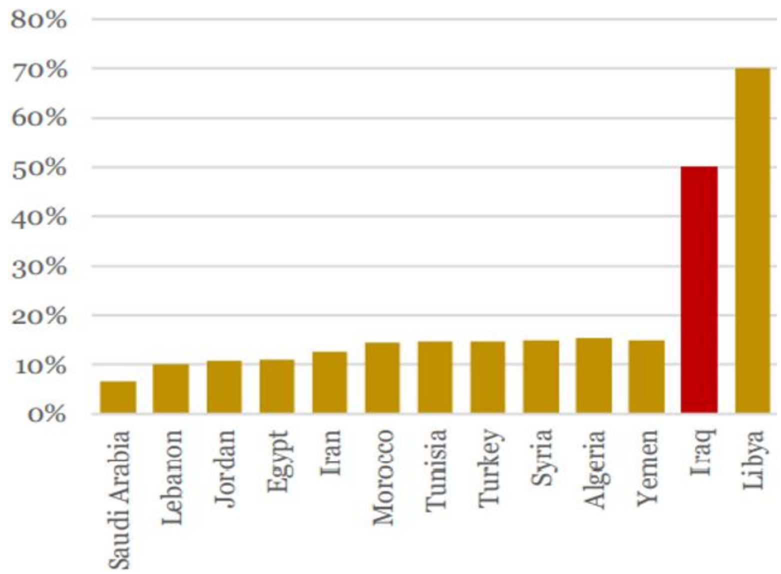


Figure 5.6. Losses in Iraq power system with other countries.

In addition to the presence of transgressing on the electricity sector, there is wrong behavior in dealing with electrical energy as the increase in electrical power outages, especially in the summer season, led in turn to an increase in citizens' participation in private generators in exchange for paying monthly bills in amperes. Where these generators are used to supply electricity to small devices with low power, and high-capacity cooling devices remain operating when the electricity of the national grid is turned on, where a large and sudden increase in loads occurs. This in turn leads to damage the circuit breakers in distribution networks.

As we mentioned in the previous item, the use of private generators is through amps, and the monthly payment costs 15,000 IQD per ampere. That is about $10. Household subscription is 8 amps at an annual cost of 1,800,000 IQD (US $1,500), but this also varies by household size. Thus, the shortfall in electrical utilities is (0.970 MWh/year) per person put a price on 1,047,600 IQD (US $873) on an average cost of a MWh of personal generators in Iraq from International Energy Agency, while request provided by the state put a price on 132,000 IQD (US $110) per year on average from resident consumer tariffs. In overall, the price of electricity is annually 1,179,600 IQD (US $983) per person. Reducing energy consumption and subsidizing the government will lead to reduce the gap between supply and demand, and reaching 100 supplies from national grid. This in turn give rise to reducing the cost to 564,000 IQD (US $470) annually. This bill is paid to the government instead of private generators at the rate of 0.1 USD/kWh. Figure 5.7 shows the yearly electricity price per person used.

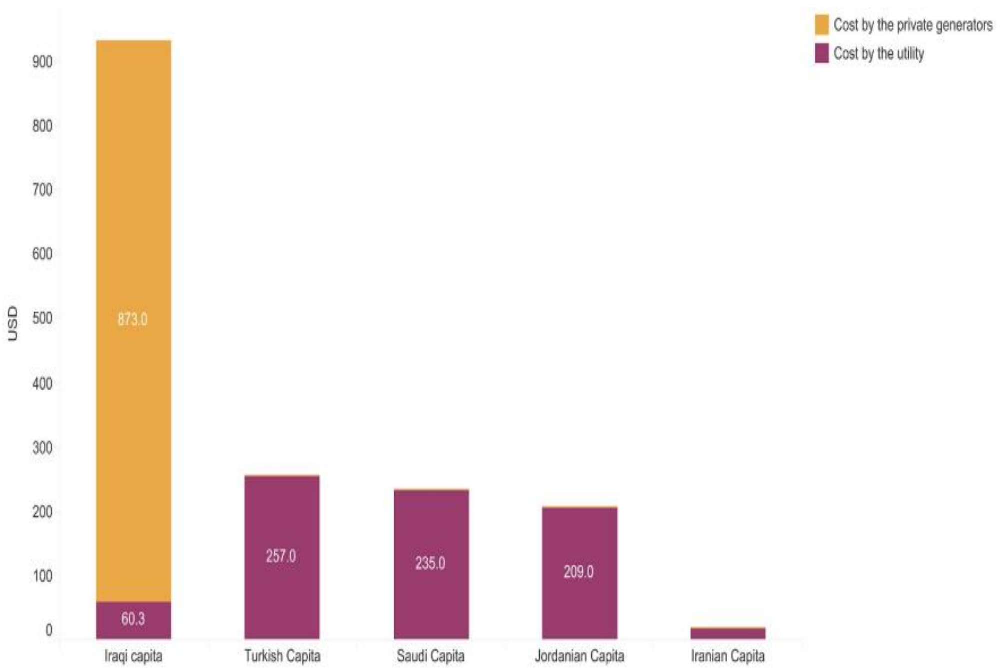


Figure 5.7. Yearly electricity price per person in USD.

Therefore, reducing losses in the distribution networks that include hackers and paying bills on the network, as well as technical losses, would generate large revenues for Iraqi Ministry of Electricity, amounting to 13 billion dollars, which would exceed government support for electricity and the use of this budget in development projects and development in all fields. Figure 5.8 compares between the cost of utility grid cost and private generator [58,60].

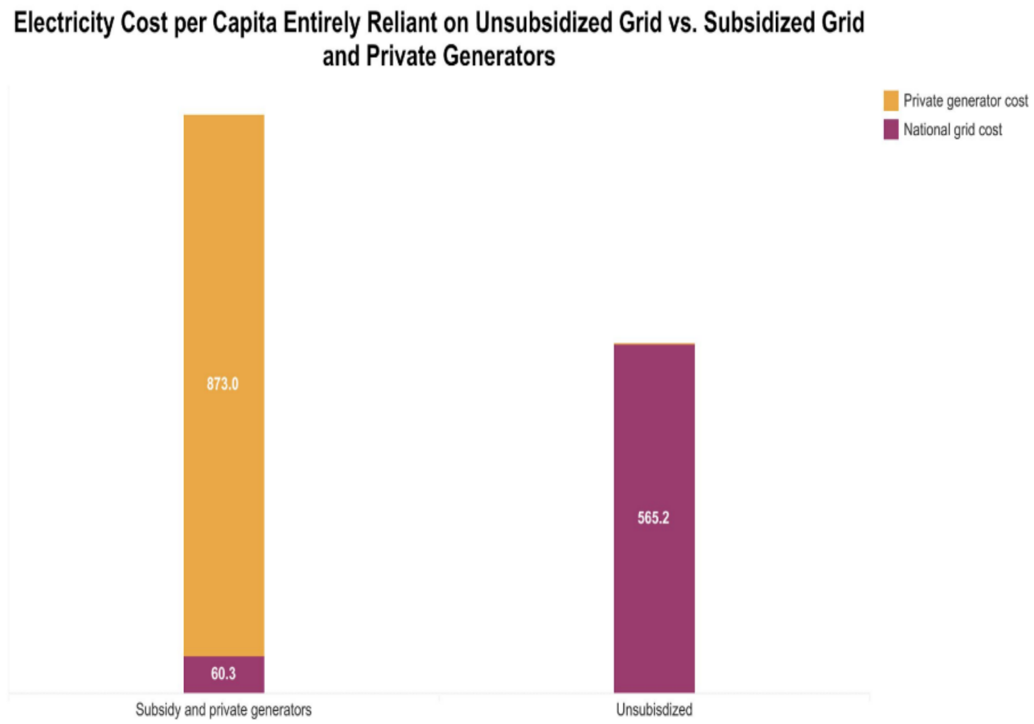


Figure 5.8. Comparison between the cost of utility grid cost and privet generator.

5.3.2. Fuel Type

According to the International Energy Agency, Iraq's production depends in the largest proportion on two types of fuel: oil and natural gas. Iraq's dependence on gas increased from 30% in 2016 to 50% in 2018 in generating electricity through Combined-Cycle Gas Turbines (CCGTs), according to statistics. Iraq burned 632 billion cubic feet of natural gas in 2019, which is the largest country in burning natural gas after Russia. Iraqi gas is produced in two ways; the first is non-associated gas, which production amounted to 4.6 billion cubic meters (BCM) per year. As for non-associated gas, Iraq's production reached ~19 BCM/yr. In 2020, the gas production sector in Iraq faced many problems represented by the lack of a strategy and equipment for extracting associated gas and the limited capacity of the pipeline networks, their progress and exposure to sabotage operations, which made most of the gas pipelines out of service [59], as there are no operations to treat the combustion of gas associated with oil extraction. In such circumstances, Iraq was forced to import gas, especially from Iran, to supply power stations operating on gas. The import of gas from Iran in 2019 amounted to 857 MMcf/d and in the first half of 2020 it reached 772 MMcf/d. Iraq's dependence on

Iranian gas in electricity production stations in Iraq reached 23% of the total electricity production. The Ministry of Electricity signed several contracts with international firms to reduce burning associated gas and its extraction by 2025 to reduce the gap between the demand for power plants and the processing of domestic gas, but some projects have stopped and regressed for political and economic reasons [60].

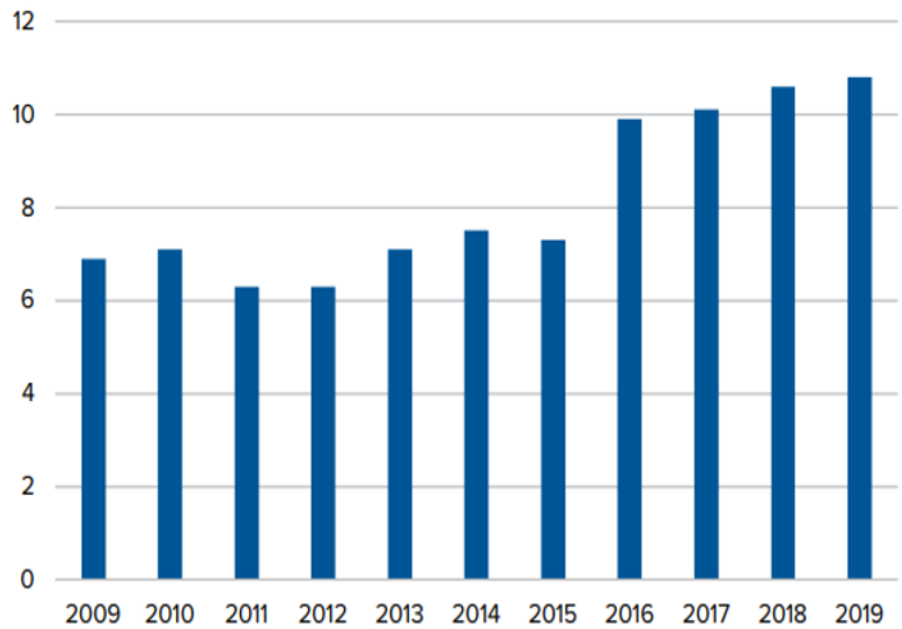


Figure 5.9. Iraq natural Gas production (2009-2019).

5.4. RENEWABLE ENERGY POTENTIAL IN IRAQ

As explained in the former passages, Iraq faces a prime problem in the electricity sector, represented by several factors, including the power outage at peak load, as well as the fuel used to operate the stations, most of which depend on traditional fuel and natural gas, despite the fact that Iraq possesses the second oil saves worldwide and also has a stockpile sufficient natural gas. On the other hand, the world is turning to use renewable energy, as the use of traditional fuels faces problems of depletion as well as environmental pollution and global warming, as the production of renewable energy on earth is increasing significantly, and it is expected that the capacity generated from renewable energy will reach about 50% in The European Union, 30% in Japan and China, and more in the United States and India, by comparing to that the energy generated by the dependence on coal is less than 15% outside Asia [61], where the use of conventional fuels in power plants will lead to air pollution as well as global warming. Figure 5.10 illustrates the renewable capacity generation in 2020.

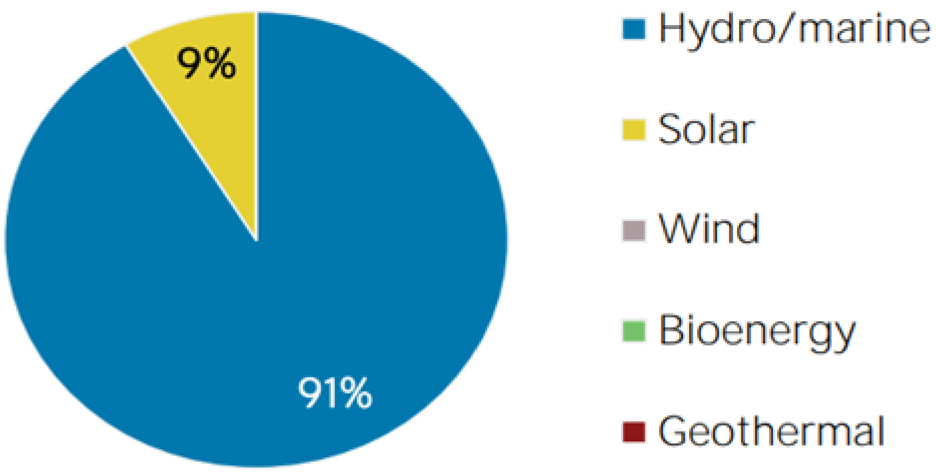


Figure 5.10. Renewable capacity generation in Iraq in 2020 [73].

There are different renewable energy resources on earth like wind energy, solar panels, hydropower plants, underground, etc.

Iraq is located within the Eastern Mediterranean countries between latitudes 29^0 and 37^0 degrees north and occupies a space of 437,071 km^2. Iraq's need for the improvement of renewable energy section to compensate for the shortage in electricity supply and reduce dependence on traditional fuels prompted researchers to focus on renewable energies that are available at lower costs, ease of installation, maintenance, and the continuity as a reliable supply [62].

Rivers are one of renewable sources in Iraq. Considering that they contain two large rivers, large projects have been established on them to store water and generate electric power. Table 5.2 contains the established dams and the capacity of electric power stations. Electricity contributes about 7.2% of a full load of electric power production in Iraq [62].

Table 5.2. Hydroelectric dams operated in Iraq [62].

Sort	Plant	No of Units	Installed Unit Size (MW)	Installed Storage Capacity (MW)
Including Storage Reservoir	Mosul Main	4	187.5	750
	Haditha	6	110	660
	Dukan	5	80	400
	Darbandikhan	3	83	249
	Himreen	2	25	50
Including Limited Storage	Mosul Regulating	4	15.0	60
	Samarra barrage	3	28.0	84
	Hindiyah barrage	4	3.750	15
	Kufa barrage	4	1.250	5

Despite the existence of those projects on these dams, they suffer from old equipment, lack of maintenance, and high maintenance costs. In addition, the main rivers suffer from a lack of water flow due to the construction of dams in neighboring countries, as well as the lack of rainfall, which has reduced the levels of the two rivers to less than 50%. From the quantities of runoff, and thus the stock of the dams has become insufficient to generate electricity, as the designed capacity is 5 GW, while the supply of these dams is estimated at 1.5 GW. Therefore, the energy generation of water is not feasible in future [62,63]. The utilization of wind energy to generate electricity requires consideration of factors; the wind speed seems to be the most significant, according to Atlas Global. Table 5.3 shows wind speed distribution in 12 months in Iraq.

Table 5.3. Wind speed distribution in months in Iraq [64].

	Weibull k					Weibull c (m/s)				
Height Month	10m	30m	50m	50m (NASA)	52m	10m	30m	50m	50m (NASA)	52m
Jan	1.23	1.50	1.37	2.22	1.81	4.05	5.73	6.26	4.68	6.85
Feb	1.21	1.50	1.53	2.25	1.78	4.74	6.42	7.14	5.18	7.57
Mar	1.20	1.60	1.52	2.39	1.94	3.70	5.38	5.77	5.470	6.28
Apr	1.44	1.82	1.81	3.18	2.13	5.53	7.24	7.89	6.40	8.27
May	1.90	2.64	0.44	3.34	2.79	4.99	6.61	6.06	5.80	7.47
Jun	2.18	2.76	2.83	3.93	3.12	8.97	10.90	11.780	8.03	12.0
Jul	1.54	1.84	1.85	3.35	2.140	6.69	8.51	9.35	7.09	9.780
Aug	1.89	2.38	2.33	3.58	2.56	5.75	7.59	8.42	7.00	8.70
Sep	1.51	1.84	1.65	2.86	1.98	4.37	6.12	6.63	5.95	7.03
Oct	1.50	1.82	1.66	2.71	1.98	4.48	6.15	6.73	5.68	7.09
Nov	1.45	1.74	1.59	2.33	1.99	3.75	5.23	5.75	4.39	6.16
Dec	1.21	1.55	1.43	2.41	1.85	3.65	5.27	5.83	4.94	6.34
All	1.36	1.69	1.63	2.53	1.93	4.97	6.71	7.34	5.89	7.77

Table 5.4. Classifications of wind turbine density at fifty m [64].

Wind Power group	Rating	Average Annual Wind Speed (m/s)	Wind Power Density (W/m^2)
1	Poor	≤5.60	≤200.0
2	Marginal	5.60-6.40	200.0-300.0
3	Fair	6.40-7.00	300.0-400.0
4	Good	7.00-7.50	400.0-500.0
5	Excellent	7.50-8.00	500.0-600.0
6	Outstanding	8.00-8.80	600.0-800.0
7	Superb	8.80-11.90	800.0-2000.0

A wind turbine globally needs a wind speed ranging from IEC61400-1, also the Wind Energy Resource Atlas of the US was formed and recorded in the National Renewable Energy Laboratory (NREL), so according to the table it crosses, not all of Iraq's geography is suitable for wind energy [64,65].

Iraq is in the southern northern side on earth. Yet, it is affected by the incidence's angle of sun's rays on ground, besides the quantity of radiation and number of day's hours that are long in summer, about 14 hours, and shortened in winter that are about 10 hours [61].

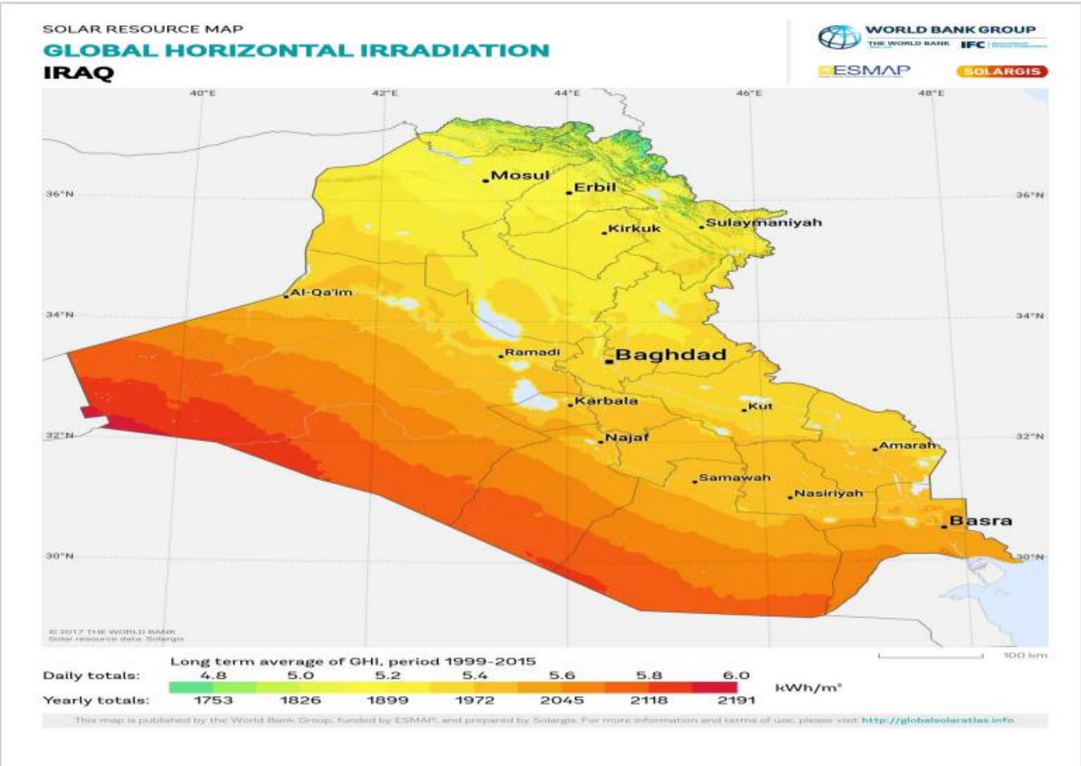
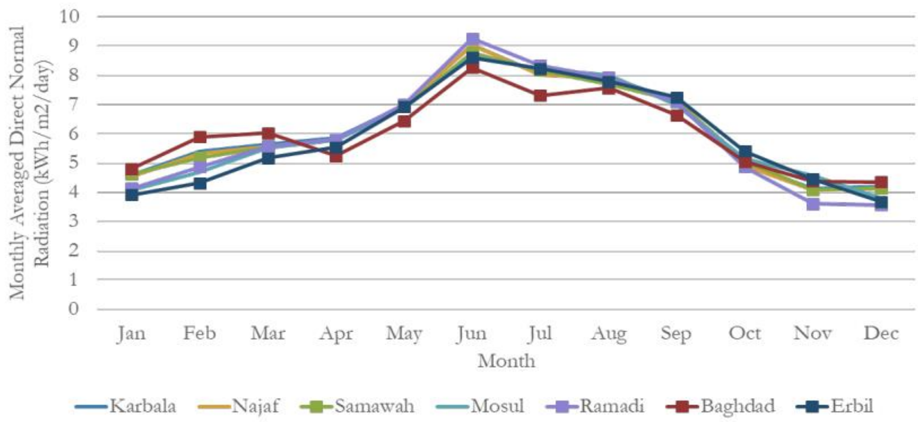


Figure 5.11. Irradiation map of Iraq [65].

Iraq has a long daylight period on a yearly base, it gathers higher than three thousands hours of solar radiation in Baghdad, the intensity of radiation hours changes from 416 W/m2 to 833 W/m2 in January and July respectively, furthermore, Iraq is in an area that has a yearly mean daily energy of global solar radiation of 2000 kWh/m^2 to 2500 kWh/m^2, where it surpasses Spain as one of the monitored levels of sunlight, so it exceeds the solar energy source in a high degree, despite the lack of real direction from the government or citizens to use it compared to neighboring countries. IEA Refers to Iraq's and Arab nations' limitation of usage of renewable and solar energy, because of the abundance of traditional fuel and its availability at a more appropriate price than the prices of renewable energy, the successive governments did not put a real study of the using renewable energy and the shortage of incentive for the citizens to use renewable energy in Iraq [61]. The international and normal solar distributions are shown in Figure 5.12.



Location	Karbala	Najaf	Samawah	Mosul	Ramadi	Baghdad	Erbil
Average Annual Global Horizontal Irradiation (GHI) [kWh/m^2]	2,248	2,233	2,226	2,200	2,193	2,190	2,171

Figure 5.12. Monthly irradiation for Iraq cities [66].

Nowadays, research on solar energy is active and held up by the Ministry of Electricity (MOE), as shown in Table 5.5, and the Ministry of Science and Technology, which has worked on a variety of projects and research with a small generation capacity of up to 2-5 MW, usage in road lighting projects, as well as operating water pumps in rural locations, generating electricity by connecting the national grid through solar panels, which are costly compared to traditional fuel.

Table 5.5. Moe for exploitation in PV solar power (2017-2020) [67].

	Governorate	2017 (MW)	2018 (MW)	2019 (MW)	2020 (MW)	Total (MW)
1	Baghdad	15.0	30.0	30.0	30.0	105.0
2	Al Muthana	130.0	30.0	30.0	30.0	220.0
3	Al Najaf	100.0	50.0	50.0	50.0	250.0
4	Al Diwaniya	-	50.0	50.0	50.0	150.0
5	Dhi Qar	50.0	50.0	30.0	30.0	160.0
6	Messan	150.0	50.0	50.0	50.0	300.0
7	Al Anbar	430.0	100.0	100.0	100.0	730.0
8	Karbalaa	-	30.0	30.0	30.0	90.0
9	Wassit	75.0	30.0	30.0	30.0	165.0
10	Diyala	15.0	25.0	25.0	25.0	90.0
11	Babil	185.0	100.0	100.0	50.0	435.0
	Total	1150.0	545.0	525.0	475.0	2695.0

Iraq's usage of solar energy remains limited within very small projects, but for the foreseeable future, the Iraqi Ministry of Electricity has developed a strategy. It concentrates on extra effective utilizations of its possibility in the areas of energy generation, which is summarized in minimizing gas emissions and minimizing dependence on fuel and improving the domestic industry and employment possibilities. The aim of Iraq is to increase the portion of electricity production from renewable energy to 9.40% of the total consuming of users in Iraq in 2030 [61, ,60,68].

5.5. POSSIBLE FUTURE DIRECTION

1. Managing energy requirements as well as pushing the consumers and changing their behavior with more efficient paths that significantly affect the rate and peak loads significantly.
2. Encouraging families to erect solar panels as well as installing electricity reading meters has a significant impact in reducing the peak loads required on transmission lines and distribution networks. Distribution network upgrades will be required to allow for bi-directional flow meters and variability management.
3. Making initiatives related to installing solar energy projects in the distribution networks.

4. Expanding the participation of renewable energy in Iraqi Generation Capacity (IGC) shall reduce gas emissions and total price of bill, as they will be self-sustained in daytime.
5. Including generation distribution, such as micro-grid, in distribution networks reduces bottlenecks on transmission networks and secondary distribution networks.
6. Reforming the electricity sector in Iraq leads to a reduction in what the citizen pays of additional money, especially for private generators, after the stability of main energy system.
7. Renewing distribution networks and installing energy kits reduces losses and breakdowns, as well as facilitating the process of collecting electricity bills.
8. Technical solutions that include installing meters in medium voltage distribution networks in areas prone to theft and energy audit procedures even distribution transformers [58,60].

PART 6

ANALYSIS OF DISTRIBUTION NETWORK SYSTEMS WITH INTEGRATION OF RENEWABLE ENERGY

In this part, the study case will be explained as one of the neighborhoods from Baghdad will be selected in terms of the number of residents, monthly electrical loads, SLG of distribution network, load categories, and hours of supply interruption from the main grid. Additionally, analyzing the power flow on the distribution network by ETAP program before and after the penetration of solar energy into the distribution network to reduce feeder losses and regulate voltage. Moreover, harmonics analysis and their impact on voltage waves, reducing them by designing harmonic filters based on ETAP to reach normal operating conditions within the established limits. The last part explains the simulation results, their discussion, and the issues that have been improved.

6.1. CASE STUDY DESCRIPTION

One of the districts (Ghazaliya) in Baghdad will be a case study. Iraq's capital is Baghdad that is the second largest city in the Arab world with 8.1 million population. Located along the Tigris, It is divided into two parts by the Tigris River; one of these parts is named Al-Karkh and the other is Al-Rusafa [69].

Baghdad is the largest city, this will be reflected in electricity consumption. As it was mentioned in part 5, the consumer suffers from a supply interruption from the main grid; this issue also appears in Baghdad neighborhoods. The study of any power system requires data on generation, load demand etc. All data on electricity supply, consumption, and supply interruptions were collected from the Iraqi Ministry of Electricity-National Control Center, and a site visit was done to distribution stations, then all this data were analyzed by using Microsoft Excel. The increase in the growth of electricity consumption increased in Baghdad ranged from 42% between the years 2009-2014. Moreover, the peak loads are higher in summer than in winter season, as shown Figure 6.1, and the maximum load is between June and September due to the high temperatures and humidity and the operation of air-condition devices [70].

Figure 6.2 shows the daily load profile of Baghdad city, Table 6.1 shows the hours of supply from the main grid.

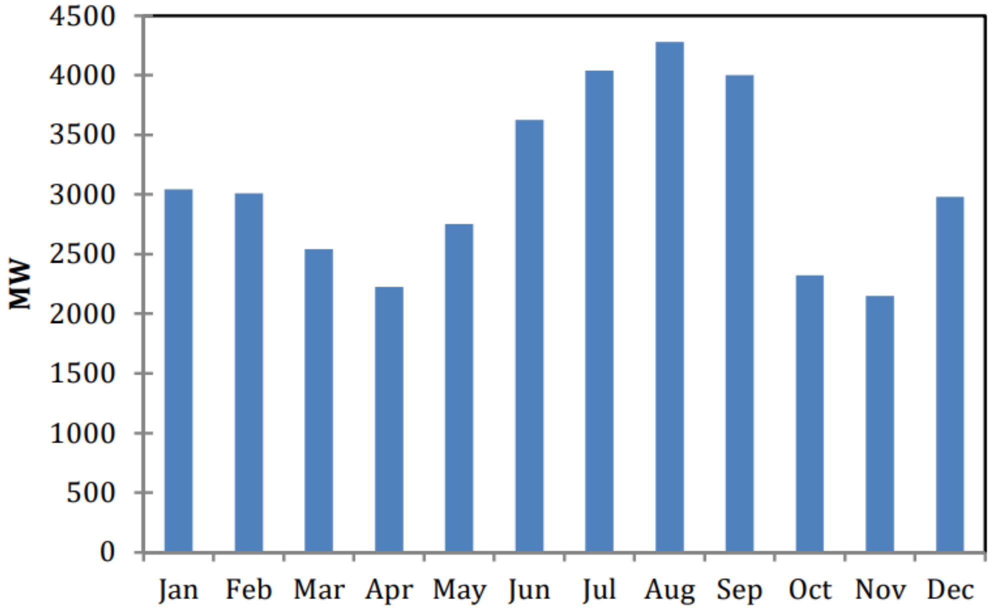


Figure 6.1. Monthly load profile of Baghdad [70].

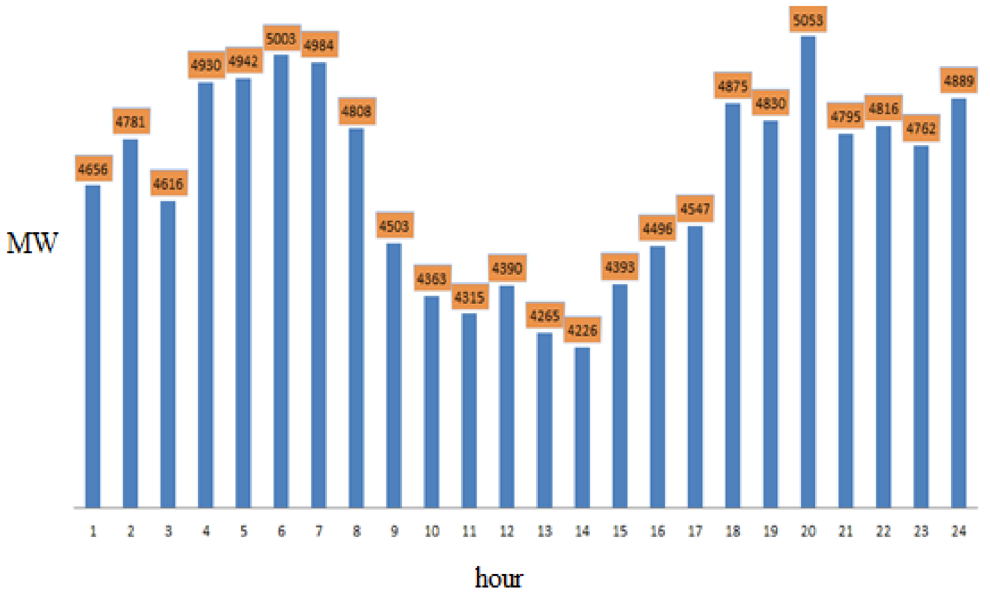


Figure 6.2. Daily load (MW) in Baghdad city (21/08/2021).

Table 6.1. Hours of supply from the main grid (MOE) [74].

City	Date	Peak demand load (MW)	Average consumer (MW)	Daily electricity supply hours (24)
Baghdad	2019	5993	4122	16 h for (22/5/2019)
	2020	Unknown	4014	13 h (2/7/2020)

One of the Iraqi capital’s neighborhoods was chosen to be a case study. Ghazaliya neighborhood is a neighborhood on the western outskirts of Al-Karkh side in Baghdad, Iraq. It is a neighborhood of about 100,000 people.

Figure 6.3. Ghazaliya neighborhood site in Baghdad city

A description of the case study will be begun with as it shows the contents of the network and its main elements, as well as the ease of dealing with it in the event of injection other sources such as renewable energy. Nevertheless, to utilize the simulation program, a SLD should be created.

Figure 6.4. Case study of feeder passing (11 kV).

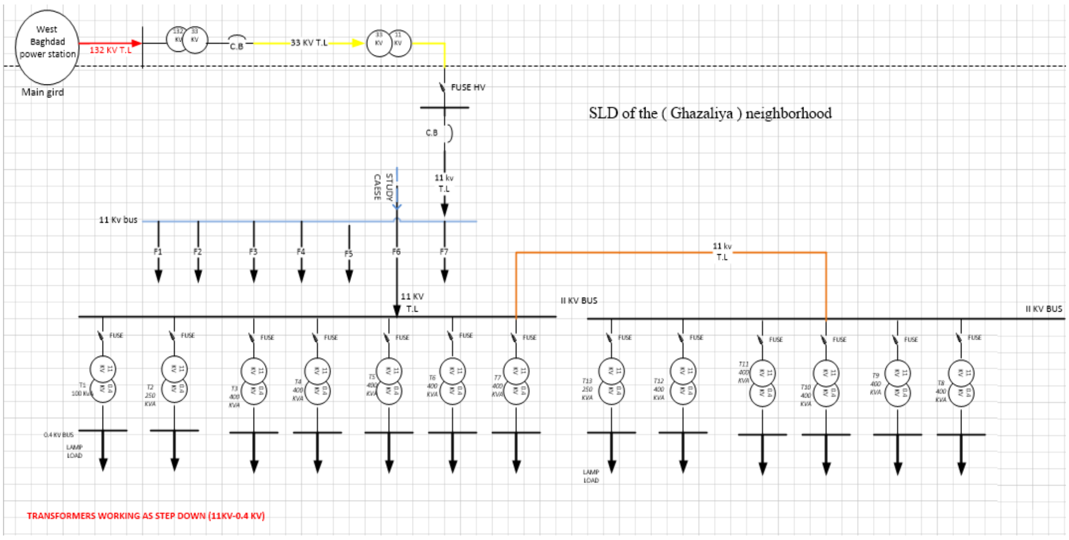


Figure 6.5. Case study - single line diagram.

1. Load Profile

The schemes 6.6 and 6.7 show the loads in the case study. It is worth noting that the maximum loads on the distribution network are divided into January for winter and August for summer, which is considered the peak loads and demand for distribution networks.

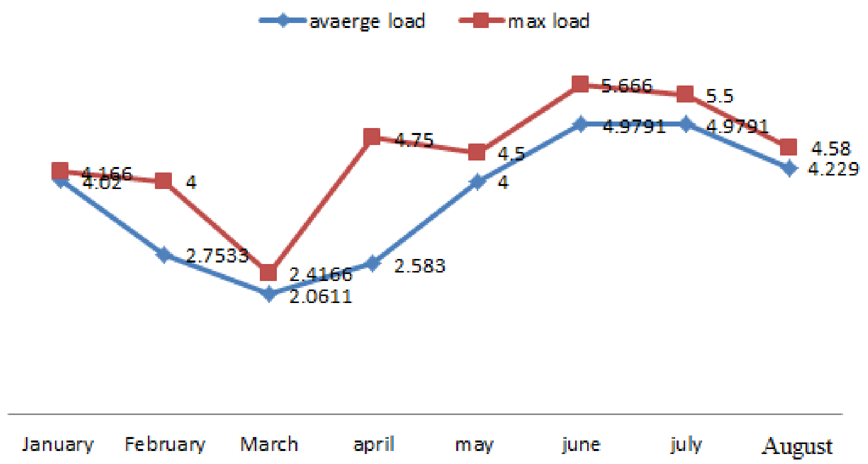


Figure 6.6. Load profile of case study in (MW) between (January –August) (2021).

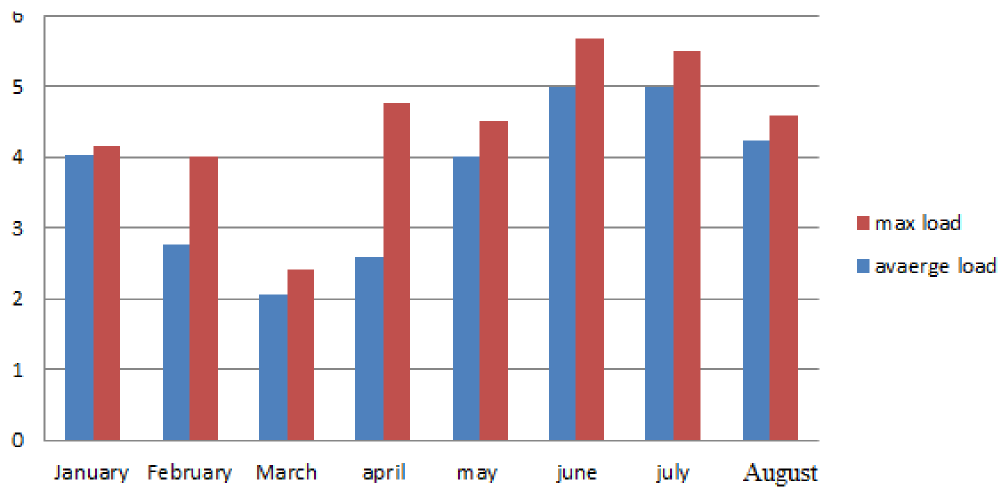


Figure 6.7. Monthly max and average load for the case study in (MW) (2021).

The main feeder is taken from a 315 MVA transformer that steps down the voltage to (33-11) kV. Also, 7 transformers of 11 kV are connected for the case study. Feeder number 6 supplies the load transformers through suspended metal transmission lines with a length of 1.5 km. An HV fuse and a circuit breaker have been added for protection, as well as to control the occurrence of faults and maintenance work.

The sixth feeder contains 13 transformers with different sizes. Table 6.2 shows the number of transformers, type of connected load, capacities, and working voltage.

Table 6.2. Transformer type and capacity.

NO.	Capacity (KVA)	Voltage Supply	Type of Load Supply	Note
1	100	11-0.4 kV	Domestic	1:1-tap changer
2	250	11-0.4 kV	Domestic	1:1-tap changer
3	400	11-0.4 kV	Domestic	1:1-tap changer
4	400	11-0.4 kV	Domestic	1:1-tap changer
5	400	11-0.4 kV	Domestic	1:1-tap changer
6	400	11-0.4 kV	Domestic	1:1-tap changer
7	400	11-0.4 kV	Domestic	1:1d-tap changer
8	400	11-0.4 kV	Domestic	1:1d-tap changer
9	400	11-0.4 kV	Domestic	1:1d-tap changer
10	400	11-0.4 kV	Domestic	1:1d-tap changer
11	400	11-0.4 kV	Domestic	1:1-tap changer
12	400	11-0.4 kV	Domestic	1:1d-tap changer
13	250	11-0.4 kV	Domestic	1:1-tap changer

6.2. DISTRIBUTION NETWORK ANALYSIS BY USING ETAP PROGRAM

ETAP program is a global commercial program used for power calculations and electrical systems analysis, and it is considered one of the comprehensive programs in power integration calculations and analysis of power systems. It contains higher than fifty functional units like power flow, calculation of short circuits, transient stability, etc. and so provides an overall and effective solution starting with planning to designing, analysis, real time operation and control in generation systems, transmission and distribution systems, and microgrid [71,72].

Simulation units for different electric parts and power system tools requested for a microgrid like photovoltaic and wind are a basic and straightforward form. The design is established simply by directly pulling the mouse, which makes the process very impressive, it is also a representation of simulation data. Once distributed, a case study design is established. Each part’s data is expressed in the design. Also, the results of simulation for every part are given as a report.

From what is concluded below, the case study for this thesis is built according to the existing data and elements, and the case study is described to build an SLD by using ETAP to simulate the power flow and harmonic analyze of the case study.

6.2.1. Load Flow Analysis

It is completed using ETAP program to know the voltage values, voltage angle, active power and reactive power, the voltage drop in its branches, and overall system losses. Table 6.5 shows the alert settings for all the elements of the case study. It was divided into critical alerts and marginal alerts. As the alert of critical values alarms the user to try to instantly adjust or correct each element's voltage drop, line load, transformer load, etc., Newton-Raphson method was used as a solution method.

Table 6.3. The default alarm load flow setting values.

Element	Critical Alert %	Marginal Alert %
Busbar under voltage	95	98
Busbar over voltage	105	102
Transformer load	95	100
Line load	100	95
Inverter/Charge	100	95

2. Load Flow Analysis (Before PV Penetration)

Once the SLD of the network is implemented in ETAP and running the power flow process to capture network data and alerts, the load flow will appear. Figure 6.8 shows the network study under load flow. The screen as presented is divided in more than one color: red, pink, yellow, and green, representing critical, marginal, normal, and operation condition respectively. The electrical load network for July was selected for the simulation process as it was considered the highest load of 4.97 MW. Figure 6.9 presents power supplied from the main grid.

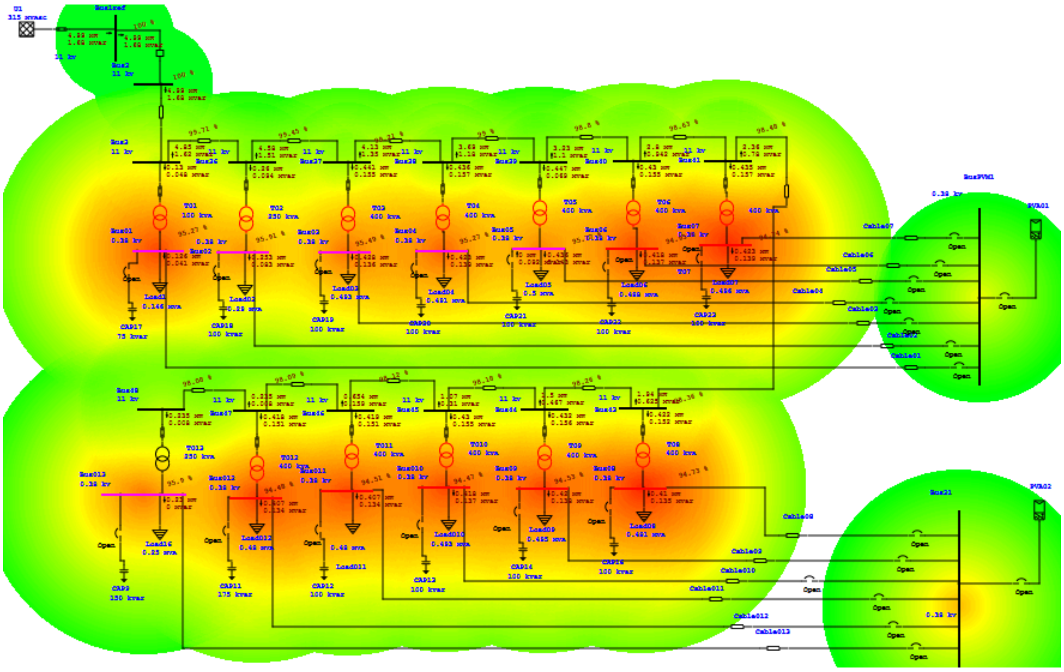


Figure 6.8. Network case study under load flow simulation before PV penetration.

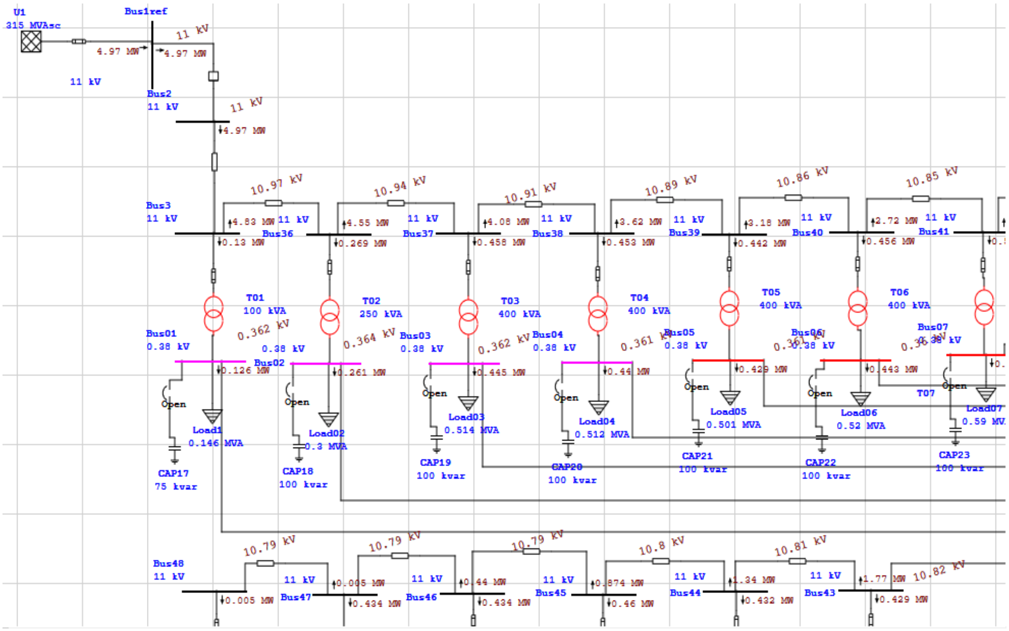
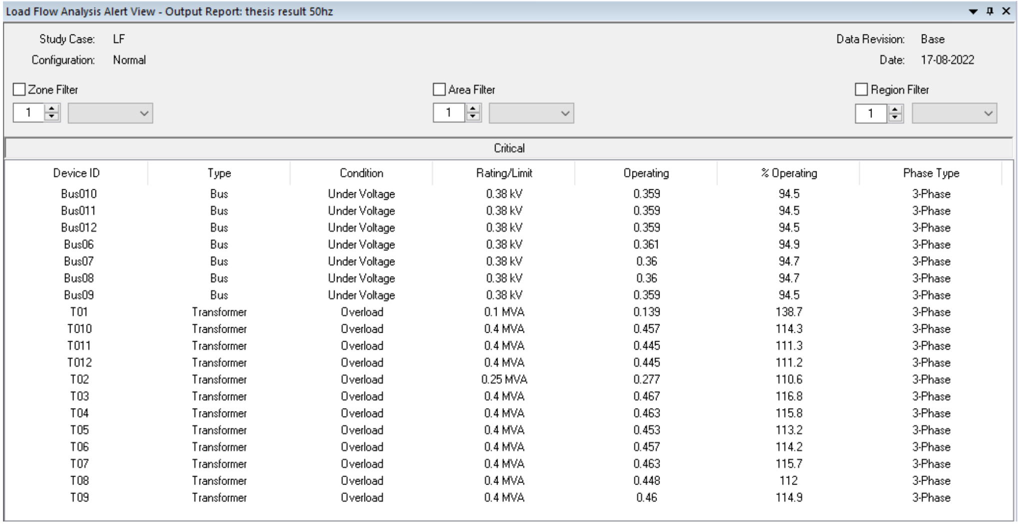


Figure 6.9. Power supplied from main grid.

1. Critical Alert



Load Flow Analysis Alert View - Output Report: thesis result 50hz

Study Case: LF — Configuration: Normal — Data Revision: Base — Date: 17-08-2022

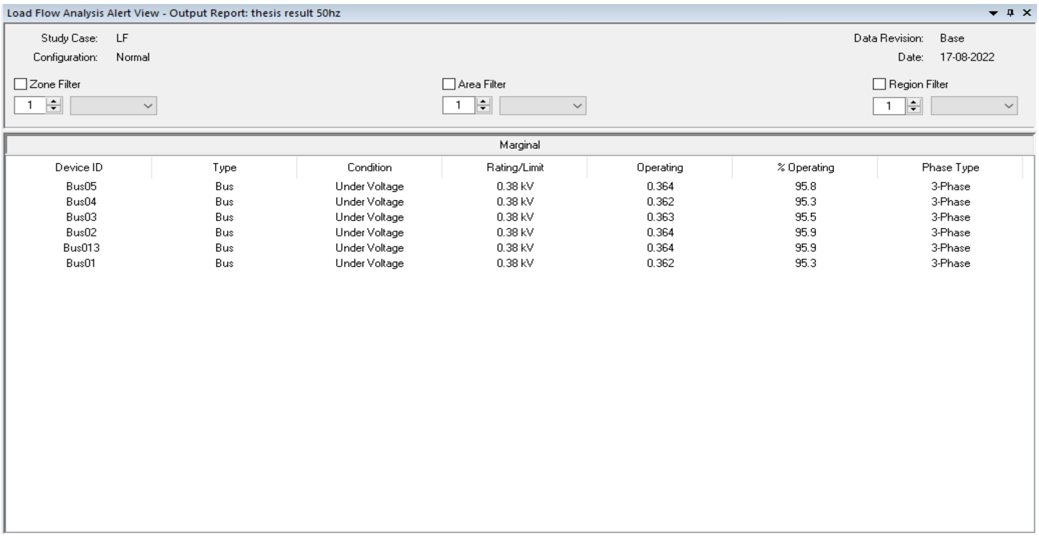
Zone Filter — Area Filter — Region Filter

Critical

Device ID	Type	Condition	Rating/Limit	Operating	% Operating	Phase Type
Bus010	Bus	Under Voltage	0.38 kV	0.359	94.5	3-Phase
Bus011	Bus	Under Voltage	0.38 kV	0.359	94.5	3-Phase
Bus012	Bus	Under Voltage	0.38 kV	0.359	94.5	3-Phase
Bus06	Bus	Under Voltage	0.38 kV	0.361	94.9	3-Phase
Bus07	Bus	Under Voltage	0.38 kV	0.36	94.7	3-Phase
Bus08	Bus	Under Voltage	0.38 kV	0.36	94.7	3-Phase
Bus09	Bus	Under Voltage	0.38 kV	0.359	94.5	3-Phase
T01	Transformer	Overload	0.1 MVA	0.139	138.7	3-Phase
T010	Transformer	Overload	0.4 MVA	0.457	114.3	3-Phase
T011	Transformer	Overload	0.4 MVA	0.445	111.3	3-Phase
T012	Transformer	Overload	0.4 MVA	0.445	111.2	3-Phase
T02	Transformer	Overload	0.25 MVA	0.277	110.6	3-Phase
T03	Transformer	Overload	0.4 MVA	0.467	116.8	3-Phase
T04	Transformer	Overload	0.4 MVA	0.463	115.8	3-Phase
T05	Transformer	Overload	0.4 MVA	0.453	113.2	3-Phase
T06	Transformer	Overload	0.4 MVA	0.457	114.2	3-Phase
T07	Transformer	Overload	0.4 MVA	0.463	115.7	3-Phase
T08	Transformer	Overload	0.4 MVA	0.448	112	3-Phase
T09	Transformer	Overload	0.4 MVA	0.46	114.9	3-Phase

Figure 6.10. Critical alert for the network case study without PV penetration.

2. Marginal Alert



Load Flow Analysis Alert View - Output Report: thesis result 50hz

Study Case: LF — Configuration: Normal — Data Revision: Base — Date: 17-08-2022

Zone Filter — Area Filter — Region Filter

Marginal

Device ID	Type	Condition	Rating/Limit	Operating	% Operating	Phase Type
Bus05	Bus	Under Voltage	0.38 kV	0.364	95.8	3-Phase
Bus04	Bus	Under Voltage	0.38 kV	0.362	95.3	3-Phase
Bus03	Bus	Under Voltage	0.38 kV	0.363	95.5	3-Phase
Bus02	Bus	Under Voltage	0.38 kV	0.364	95.9	3-Phase
Bus013	Bus	Under Voltage	0.38 kV	0.364	95.9	3-Phase
Bus01	Bus	Under Voltage	0.38 kV	0.362	95.3	3-Phase

Figure 6.11. Marginal alert for the distribution network without PV penetration.

3. Load Flow Analysis (After PV Penetration)

A single PV injection power does not provide an impression of the influence on distribution networks, so two scenarios will be used, and then a simulation will be done to show the effect of each value on the power flow data.

ETAP program allows to select the type of the solar cell and its specifications and to determine the special elements depending on the amount of irradiation, cell power, Voc, Vsc, etc. as shown in Figures 6.12 and Figure 6.13. To determine the elements of the solar cells, as well as the quantity of PV arrays and the required capacity using series and parallel connecting elements, and then determine the value of the inverter based on the required loads.

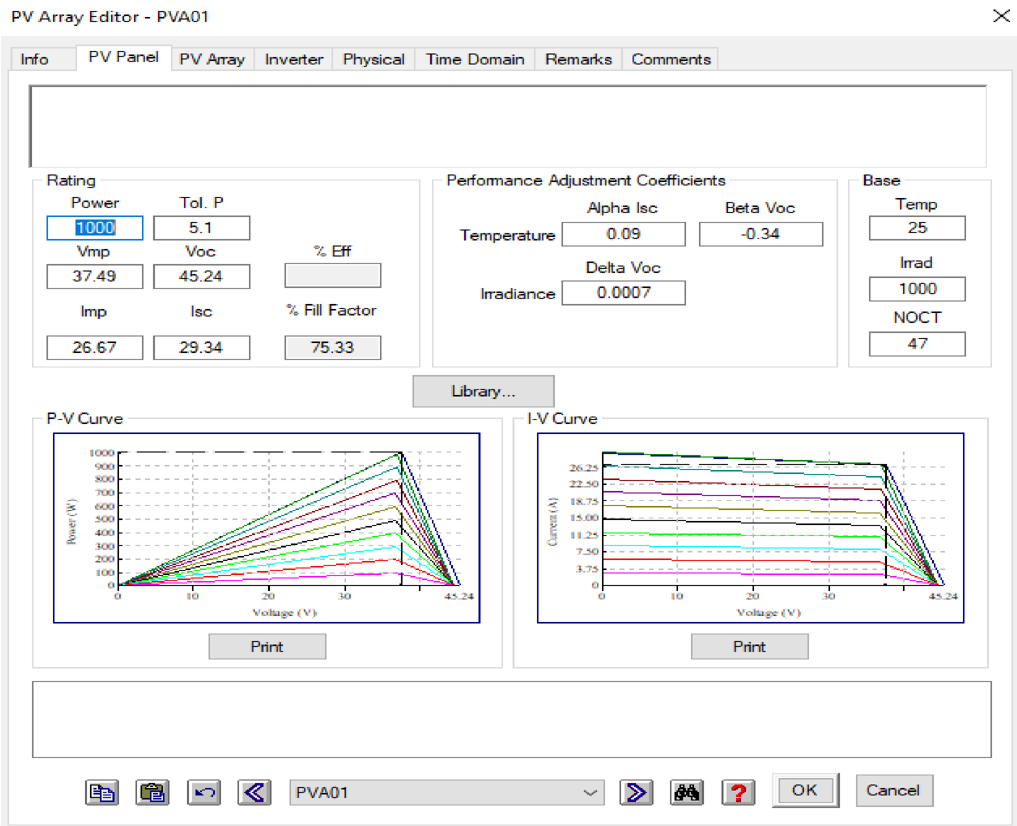


Figure 6.12. PV model characteristic and properties integrated with DN.

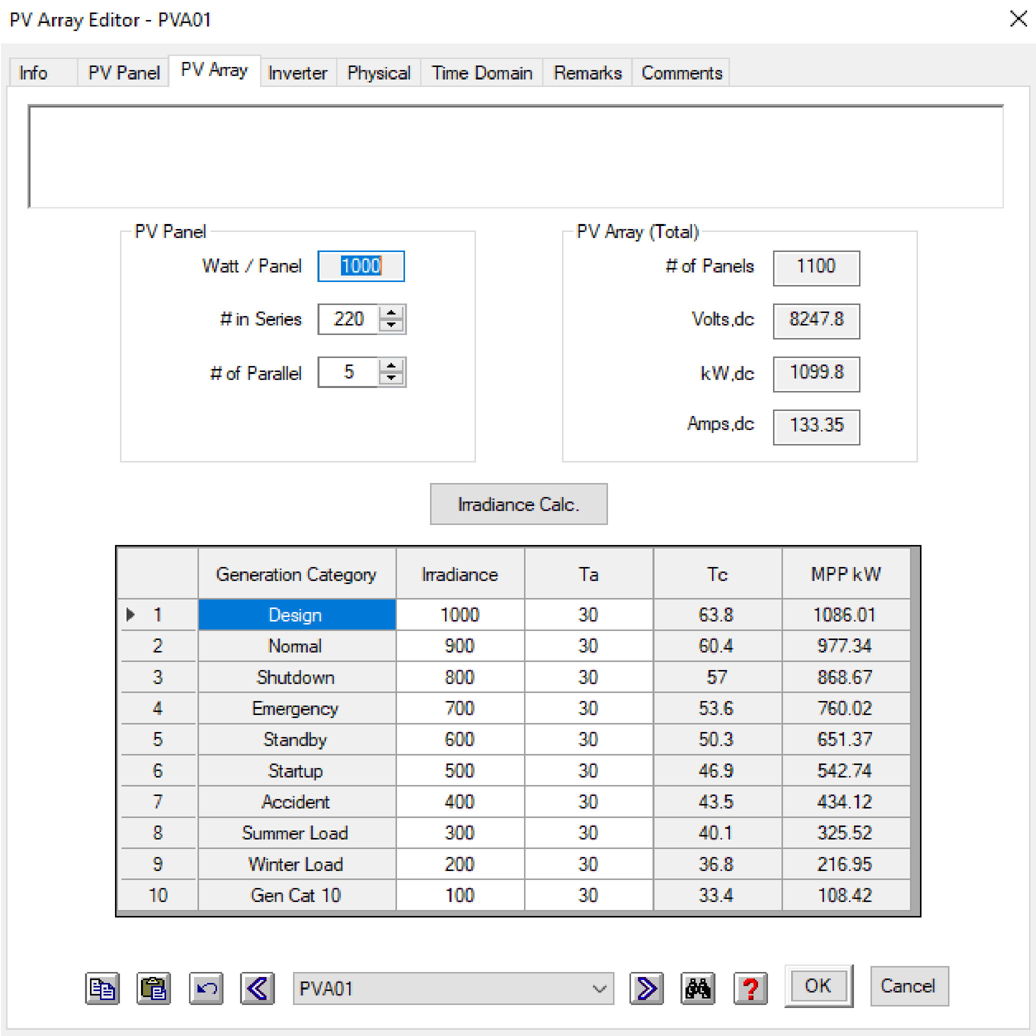
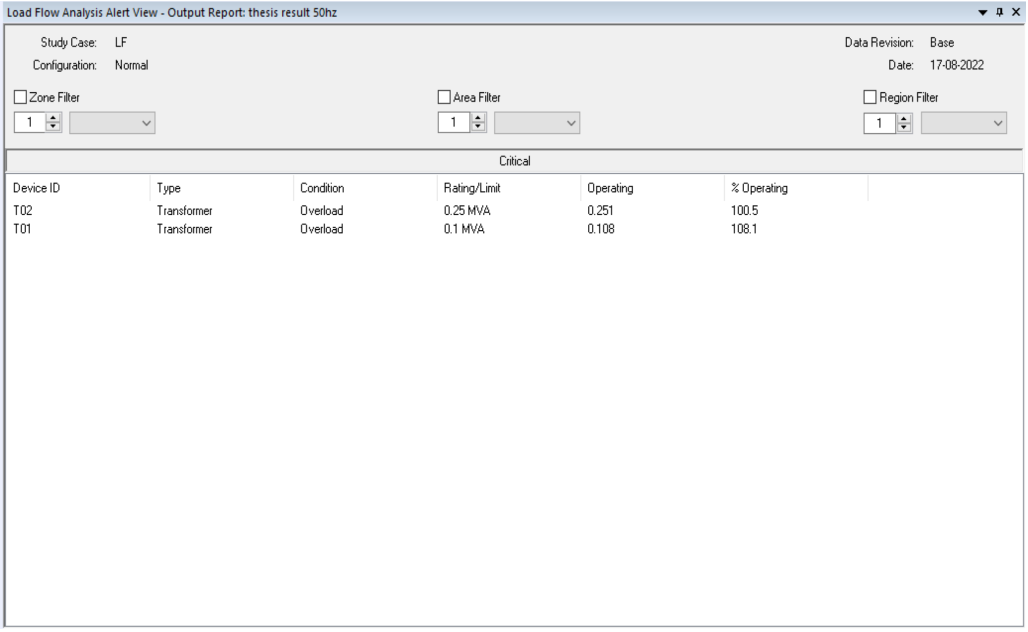


Figure 6.13. Number of PV arrays and properties integrated with DN.

The DN simulation under the ETAP software was carried out through two scenarios, which are explained as follows:

The First Scenario: Analyzing DN with 1 MW PV system integration.

An amount of 1 MW of PV will be injected into the DN after calculating its values through ETAP, then simulating and showing the results to notice the changes that will occur after 1 MW penetration into the DN, a test is being started for critical and marginal alarms as shown in Figures 6.14 and 6.15, and the reduction of critical alarms is noticed.



Load Flow Analysis Alert View - Output Report: thesis result 50hz

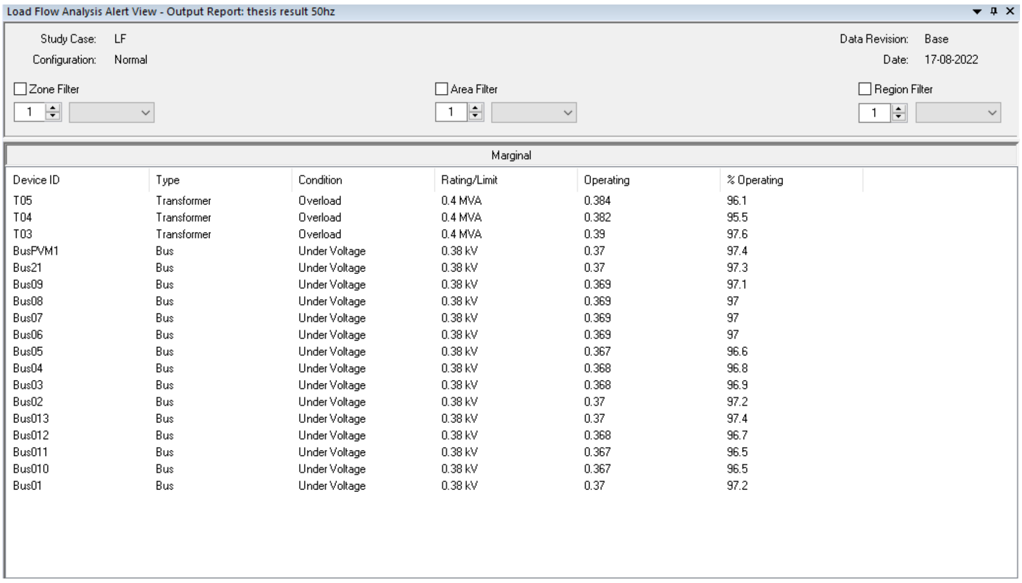
Study Case: LF
Configuration: Normal
Data Revision: Base
Date: 17-08-2022

Zone Filter 1
Area Filter 1
Region Filter 1

Critical

Device ID	Type	Condition	Rating/Limit	Operating	% Operating
T02	Transformer	Overload	0.25 MVA	0.251	100.5
T01	Transformer	Overload	0.1 MVA	0.108	108.1

Figure 6.14. Critical alert for the DN of 1 MW after PV penetration.



Load Flow Analysis Alert View - Output Report: thesis result 50hz

Study Case: LF
Configuration: Normal
Data Revision: Base
Date: 17-08-2022

Zone Filter 1
Area Filter 1
Region Filter 1

Marginal

Device ID	Type	Condition	Rating/Limit	Operating	% Operating
T05	Transformer	Overload	0.4 MVA	0.384	96.1
T04	Transformer	Overload	0.4 MVA	0.382	95.5
T03	Transformer	Overload	0.4 MVA	0.39	97.6
BusPVM1	Bus	Under Voltage	0.38 kV	0.37	97.4
Bus21	Bus	Under Voltage	0.38 kV	0.37	97.3
Bus09	Bus	Under Voltage	0.38 kV	0.369	97.1
Bus08	Bus	Under Voltage	0.38 kV	0.369	97
Bus07	Bus	Under Voltage	0.38 kV	0.369	97
Bus06	Bus	Under Voltage	0.38 kV	0.369	97
Bus05	Bus	Under Voltage	0.38 kV	0.367	96.6
Bus04	Bus	Under Voltage	0.38 kV	0.368	96.8
Bus03	Bus	Under Voltage	0.38 kV	0.368	96.9
Bus02	Bus	Under Voltage	0.38 kV	0.37	97.2
Bus013	Bus	Under Voltage	0.38 kV	0.37	97.4
Bus012	Bus	Under Voltage	0.38 kV	0.368	96.7
Bus011	Bus	Under Voltage	0.38 kV	0.367	96.5
Bus010	Bus	Under Voltage	0.38 kV	0.367	96.5
Bus01	Bus	Under Voltage	0.38 kV	0.37	97.2

Figure 6.15. Marginal alert for the DN of 1 MW after PV penetration.

The shape of the system under simulation is also noted with color alerts. Most of the equipment is left from red that is critical to marginal colors, which proves the start of improvement in operating conditions as shown in Figure 6.16.

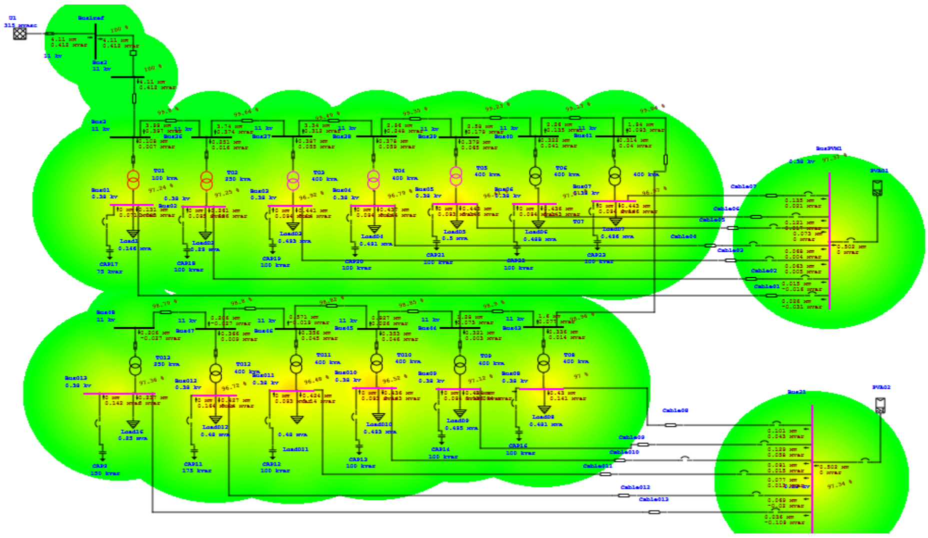


Figure 6.16. DN under simulation after (1 MW) PV penetration.

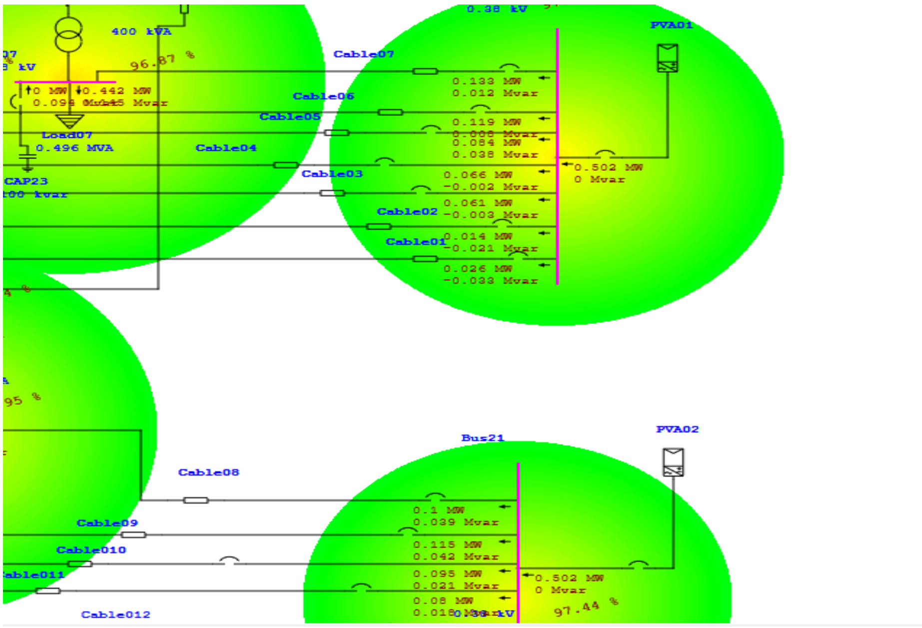
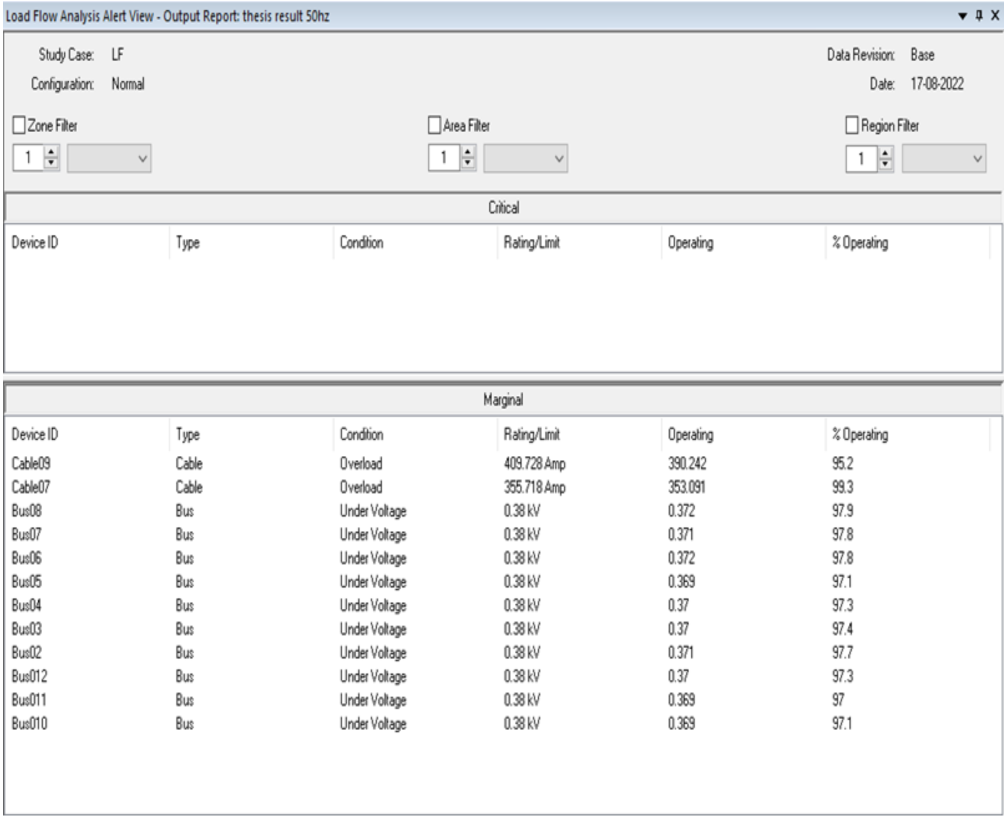


Figure 6.17. PV penetration’s capacity in DN.

The Second Scenario: Analyzing DN with 2 MW PV system integration.

Increasing the power’s amount injected into the distribution network to an estimated amount of 2 MW after a rise in the number of panels and capacity of the inverter used. The simulation is repeated to display the effect after this increase in penetration, as usual; critical and marginal alarms are obtained firstly as in Figure 6.18. The disappearance of critical alerts and the marked decrease in marginal alerts are noticed.



Load Flow Analysis Alert View - Output Report: thesis result 50hz

Study Case: LF | Data Revision: Base
Configuration: Normal | Date: 17-08-2022

Zone Filter | Area Filter | Region Filter

Critical

Device ID	Type	Condition	Rating/Limit	Operating	% Operating

Marginal

Device ID	Type	Condition	Rating/Limit	Operating	% Operating
Cable09	Cable	Overload	409.728 Amp	390.242	95.2
Cable07	Cable	Overload	355.718 Amp	353.091	99.3
Bus08	Bus	Under Voltage	0.38 kV	0.372	97.9
Bus07	Bus	Under Voltage	0.38 kV	0.371	97.8
Bus06	Bus	Under Voltage	0.38 kV	0.372	97.8
Bus05	Bus	Under Voltage	0.38 kV	0.369	97.1
Bus04	Bus	Under Voltage	0.38 kV	0.37	97.3
Bus03	Bus	Under Voltage	0.38 kV	0.37	97.4
Bus02	Bus	Under Voltage	0.38 kV	0.371	97.7
Bus012	Bus	Under Voltage	0.38 kV	0.37	97.3
Bus011	Bus	Under Voltage	0.38 kV	0.369	97
Bus010	Bus	Under Voltage	0.38 kV	0.369	97.1

Figure 6.18. Critical alert and marginal alert after 2 MW PV penetrations.

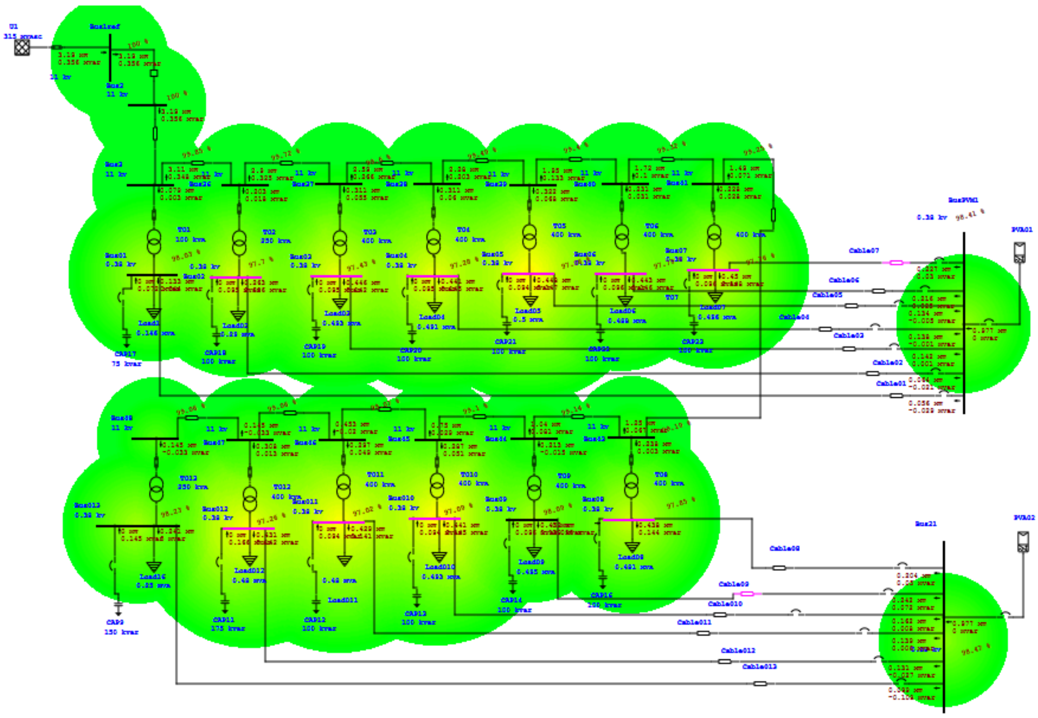


Figure 6.19. Network case study after 2 MW PV penetration.

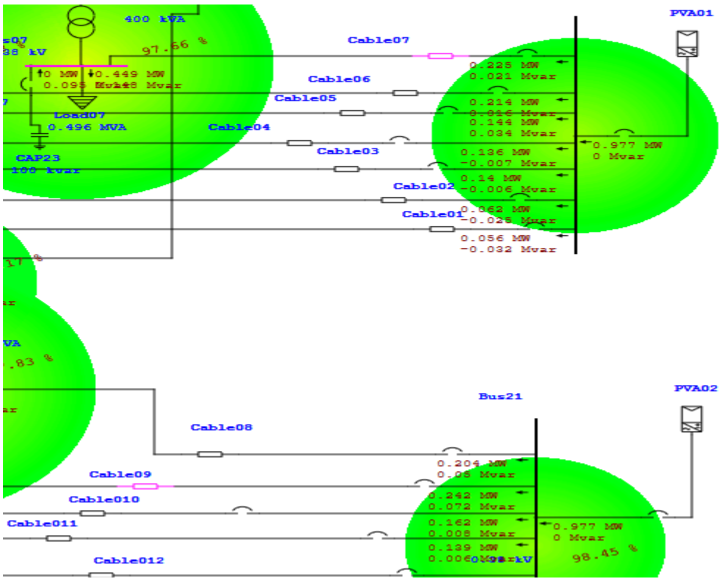


Figure 6.20. Capacity of the PV penetration in the DN.

After simulating the power flow under the color alerts, a decrease was noticed in the supply value of the main grid from 4.97 MW to 3.1 MW after the injection of PV system, as well as most of the elements and dangerous circuits that cause equipment damage in the distribution network exited from the critical alert. The important thing is to expand the amount for renewable energy penetration and the consequent reduction of losses, optimization of voltage, eliminating additional loads on devices, etc., which will be illustrated through charts and spreadsheets by power flow simulation.

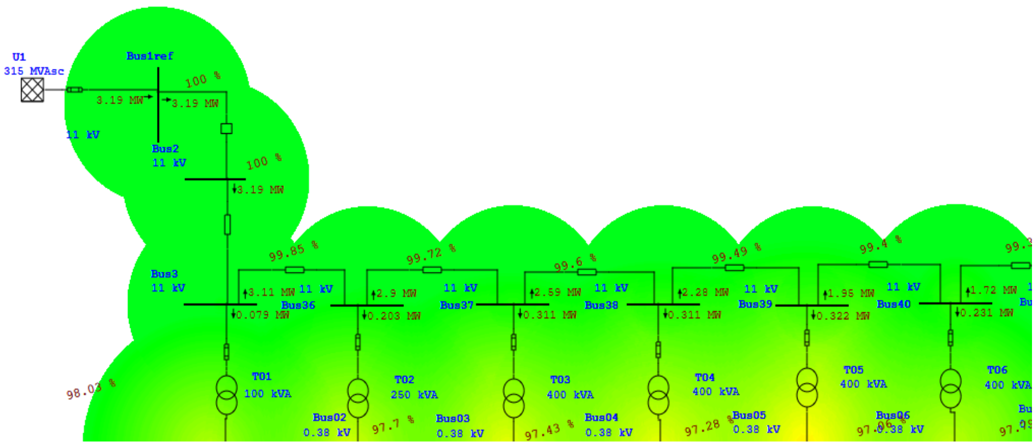


Figure 6.21. Power supplied from main grid reduces after PV penetration.

6.3. HARMONIC ANALYSIS

As mentioned in parts 2 and 3, the integration of distribution generators into power systems increases their complexity. In this part, the harmonics analysis of the distribution networks will be dealt with considering that the distribution generators are a photovoltaic system integrated with the main grid. This analysis is done by ETAP.

Harmonics sources are inverters used in renewable energy resources like solar and wind, as well as saturated power transformers, and when these sources are considered rich sources of harmonics, distortion of the voltage wave occurs that may exceed the permissible limit (IEEE 519).

ETAP allows for accurate analysis of harmonics and requires information from the main network and microgrid sources. This analysis is important in knowing the amount of THD besides the possibility of designing filters commensurate with the harmonics to improve them and thus get rid of the harm that they may cause.

Putting the distribution network in ETAP and choosing the harmonics analysis requires the following:

1. Load magnitude.
2. The selection of the busbar number.
3. Immediate power factor of the load.

Figure 6.22 shows a distribution network and the steps involved in analyzing the harmonics.

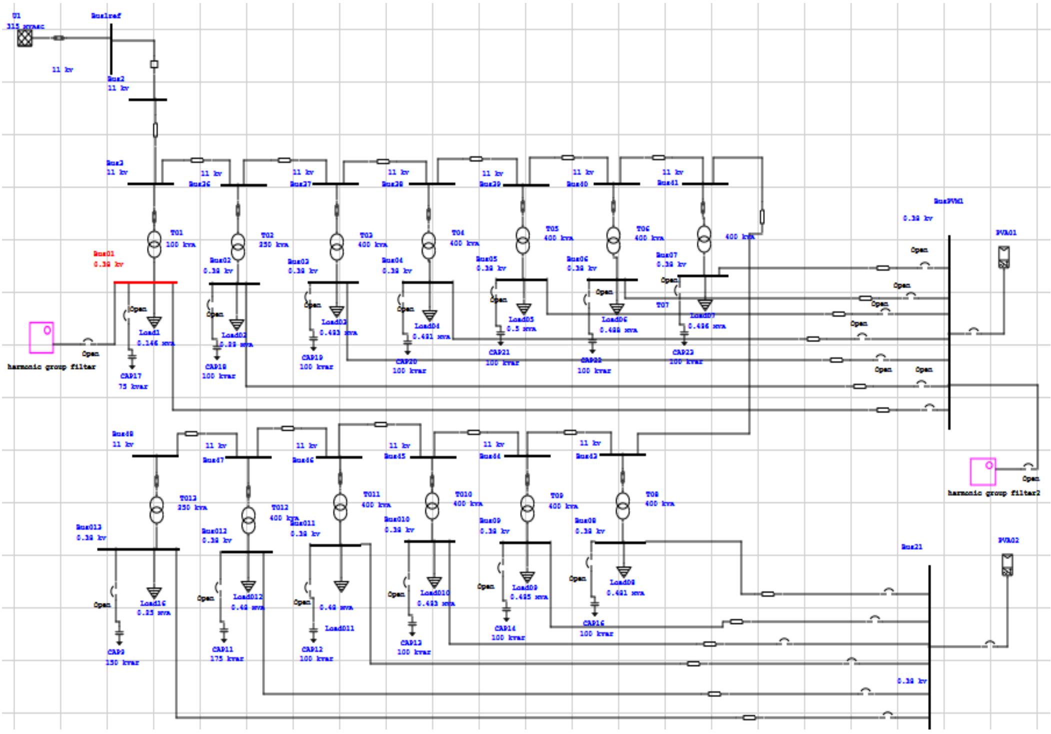


Figure 6.22. Network case study in ETAP for harmonic analysis.

To facilitate the process of conducting harmonics analysis, a single bus is selected. The source of the harmonics is focused on it to know the amount of THD. Additionally, the harmonic filter, the steps of designing and selecting the appropriate filter to reach the permissible limit of (IEEE 519) as follows.

The first step is to select the harmonics sources for each of the transformer and the inverter, where ETAP program provides several options for choosing the source of the harmonics as shown the Figure 6.23.

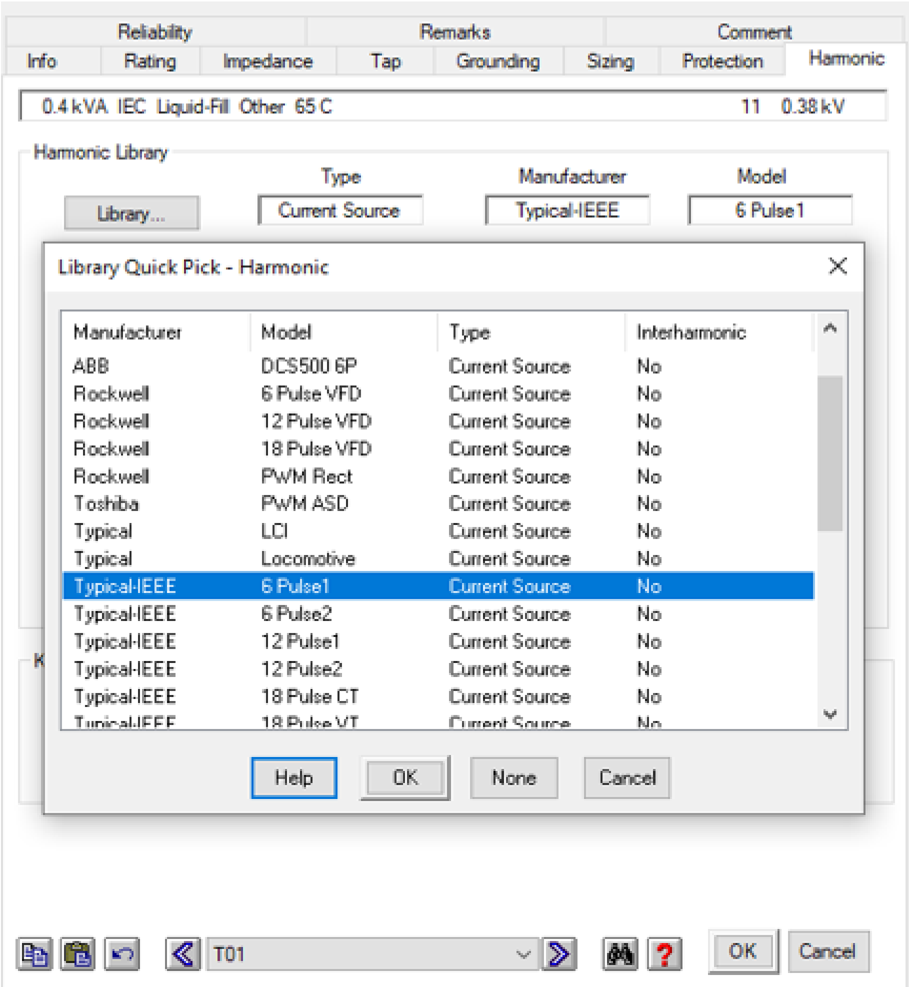


Figure 6.23. Choosing harmonic source.

Selecting harmonic source from ETAP program library for each of the inverters in the solar energy system and the transformers as Figures 6.24 and 6.25.

1. Current source - 6 pulse 1 for inverter.
2. Current source - 6 pulse 1 for power transformer.

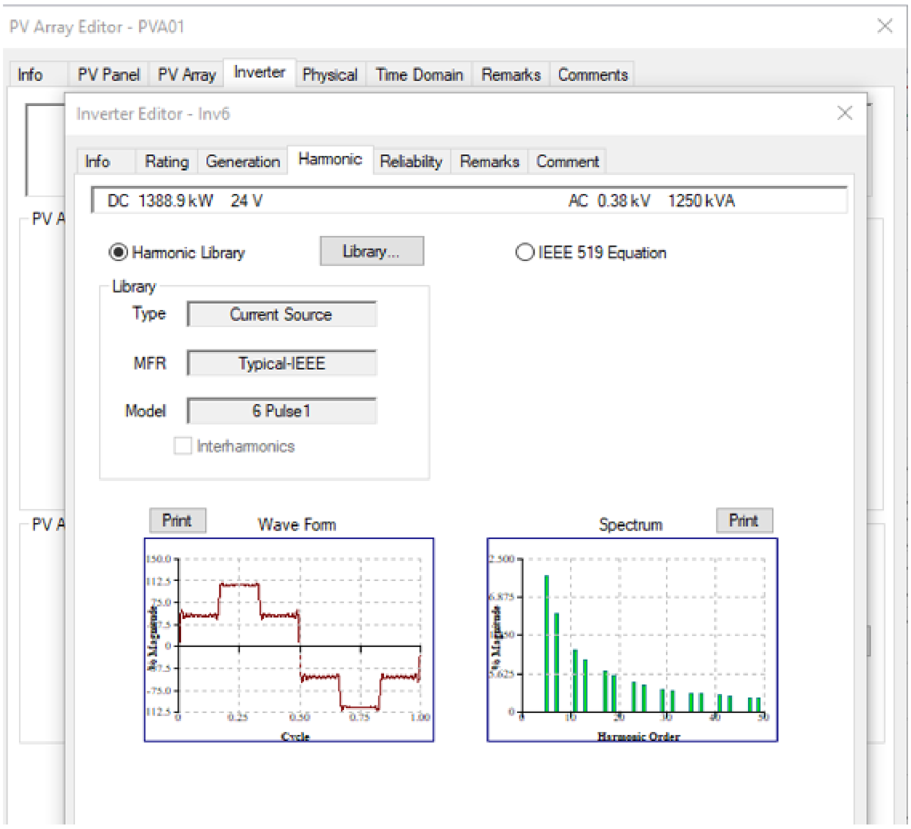


Figure 6.24. Selecting harmonic source of the inverter.

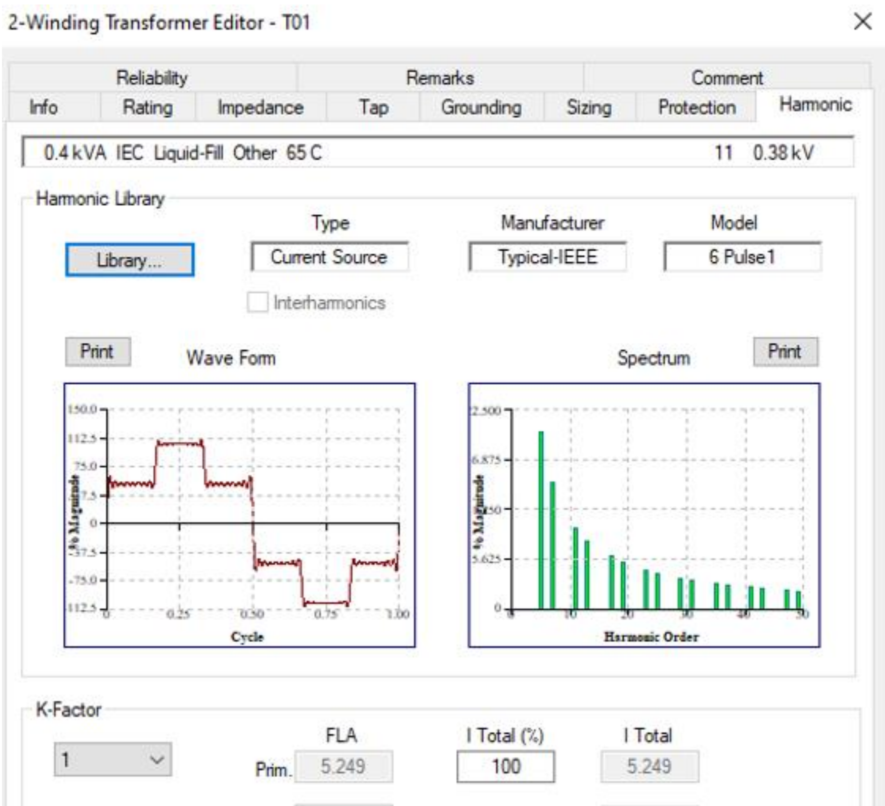


Figure 6.25. Selecting harmonic source of the power transformer.

After that, Bus 1 was chosen as a sample to do the harmonic analysis on, where the load value is 0.146 MW and power factor is 95% as illustrated in Figure 6.26.

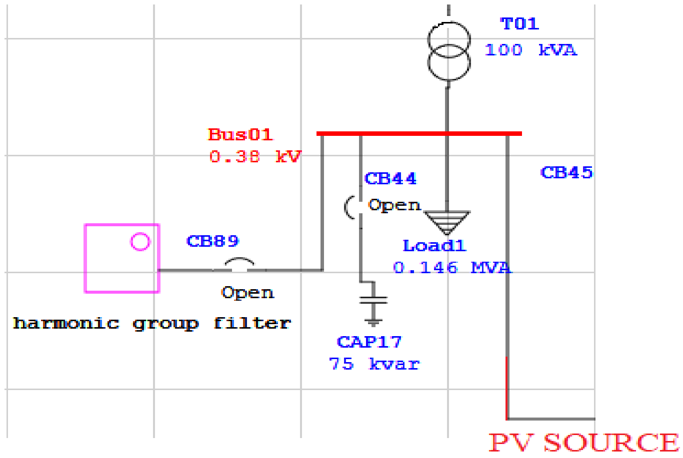
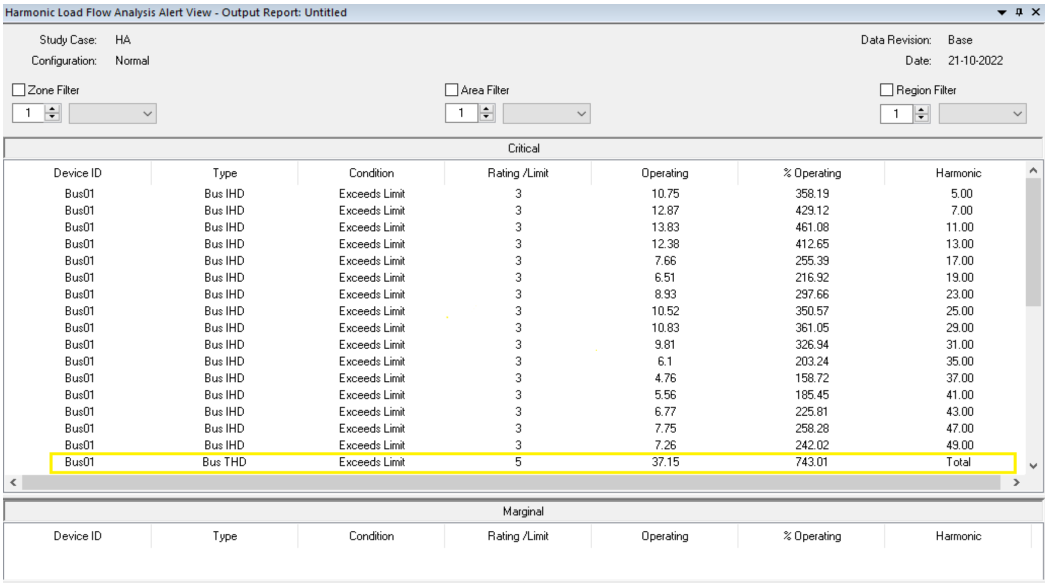


Figure 6.26. Bus 1 from case study to make harmonic analysis.

After the analysis, the following results appeared, and the value of the total distortion (THD) was shown in critical alarm part. Figure 6.27 presents the THD value that is 37.15% which is a limit that exceeds what is allowed by (IEEE 519).



Harmonic Load Flow Analysis Alert View - Output Report: Untitled

Study Case: HA
Configuration: Normal
Data Revision: Base
Date: 21-10-2022

Zone Filter 1
Area Filter 1
Region Filter 1

Critical

Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic
Bus01	Bus IHD	Exceeds Limit	3	10.75	358.19	5.00
Bus01	Bus IHD	Exceeds Limit	3	12.87	429.12	7.00
Bus01	Bus IHD	Exceeds Limit	3	13.83	461.08	11.00
Bus01	Bus IHD	Exceeds Limit	3	12.38	412.65	13.00
Bus01	Bus IHD	Exceeds Limit	3	7.66	255.39	17.00
Bus01	Bus IHD	Exceeds Limit	3	6.51	216.92	19.00
Bus01	Bus IHD	Exceeds Limit	3	8.93	297.66	23.00
Bus01	Bus IHD	Exceeds Limit	3	10.52	350.57	25.00
Bus01	Bus IHD	Exceeds Limit	3	10.83	361.05	29.00
Bus01	Bus IHD	Exceeds Limit	3	9.81	326.94	31.00
Bus01	Bus IHD	Exceeds Limit	3	6.1	203.24	35.00
Bus01	Bus IHD	Exceeds Limit	3	4.76	158.72	37.00
Bus01	Bus IHD	Exceeds Limit	3	5.56	185.45	41.00
Bus01	Bus IHD	Exceeds Limit	3	6.77	225.81	43.00
Bus01	Bus IHD	Exceeds Limit	3	7.75	258.28	47.00
Bus01	Bus IHD	Exceeds Limit	3	7.26	242.02	49.00
Bus01	Bus THD	Exceeds Limit	5	37.15	743.01	Total

Marginal

Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic

Figure 6.27. Harmonic critical alert for Bus 1.

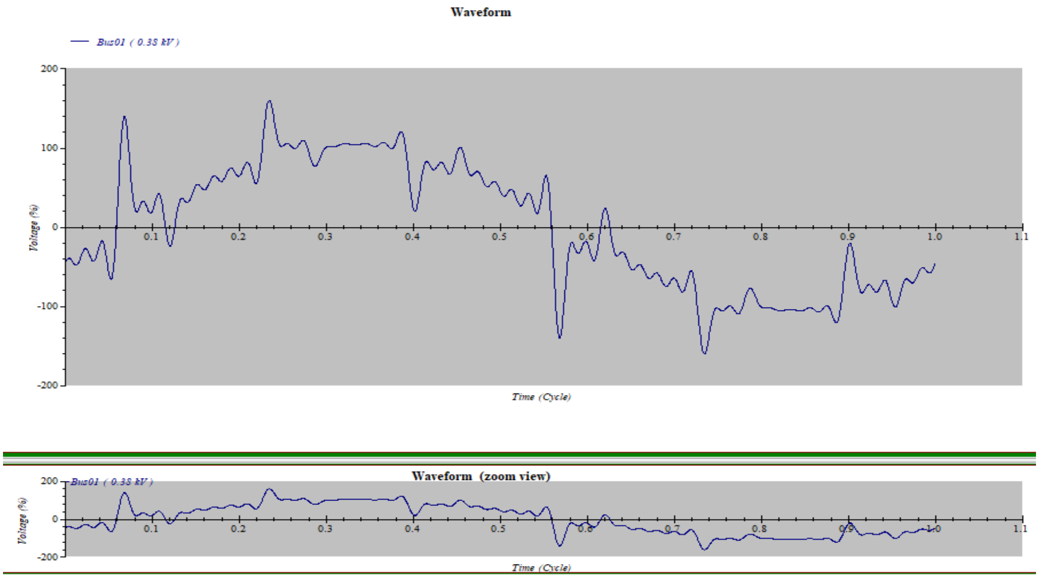


Figure 6.28. Waveform's distortion caused by distorted sources.

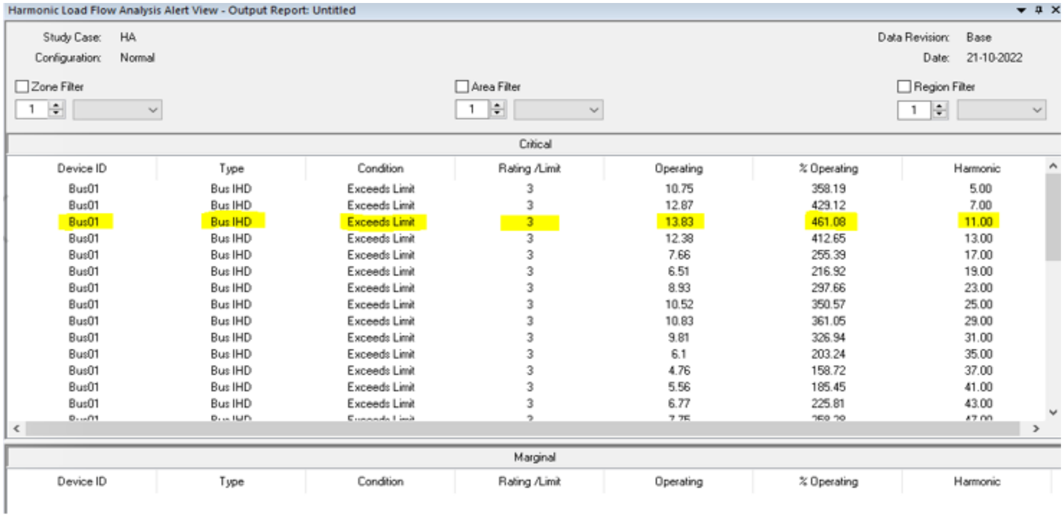
6.3.1. Harmonic Filter Design

In the third part, it was mentioned that one of the factors which reduce the effect of harmonics is harmonic filter, it is considered the most appropriate solution for all cases of distortion. ETAP program offers the possibility of designing filters and their order by analyzing the harmonics process after knowing the value of the harmonic current order and the number of harmonic orders, filling the data through the filter properties to find its size, additionally.

An analysis was performed on the comparison between the previous cases and after the filters are injected, the process will be repeated until an acceptable level of harmonics is reached. In general, SLF is the simplest and most widely used type of filter because of its low cost and it could be chosen from the program library.

For setting its required properties, the following steps should be done:

Firstly, after reading the critical alerts, the highest harmonic order that caused distortion in the alerts table must be noticed. The order of the harmonic (11) is the highest one as shown in Figure 6.29.



Harmonic Load Flow Analysis Alert View - Output Report: Untitled

Study Case: HA
Configuration: Normal
Data Revision: Base
Date: 21-10-2022

Zone Filter
Area Filter
Region Filter

Critical

Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic
Bus01	Bus IHD	Exceeds Limit	3	10.75	358.19	5.00
Bus01	Bus IHD	Exceeds Limit	3	12.87	429.12	7.00
Bus01	Bus IHD	Exceeds Limit	3	13.83	461.08	11.00
Bus01	Bus IHD	Exceeds Limit	3	12.38	412.65	13.00
Bus01	Bus IHD	Exceeds Limit	3	7.66	255.39	17.00
Bus01	Bus IHD	Exceeds Limit	3	6.51	216.92	19.00
Bus01	Bus IHD	Exceeds Limit	3	8.93	297.66	23.00
Bus01	Bus IHD	Exceeds Limit	3	10.52	350.57	25.00
Bus01	Bus IHD	Exceeds Limit	3	10.83	361.05	29.00
Bus01	Bus IHD	Exceeds Limit	3	9.81	326.94	31.00
Bus01	Bus IHD	Exceeds Limit	3	6.1	203.24	35.00
Bus01	Bus IHD	Exceeds Limit	3	4.76	158.72	37.00
Bus01	Bus IHD	Exceeds Limit	3	5.56	185.45	41.00
Bus01	Bus IHD	Exceeds Limit	3	6.77	225.81	43.00

Marginal

Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic

Figure 6.29. Exceed limits harmonic order.

Secondly, by using the harmonic order slider as in Figure 6.30, the value of the current passing to Bus 1 in harmonic order (11) is noted, which represents the harmonic current.

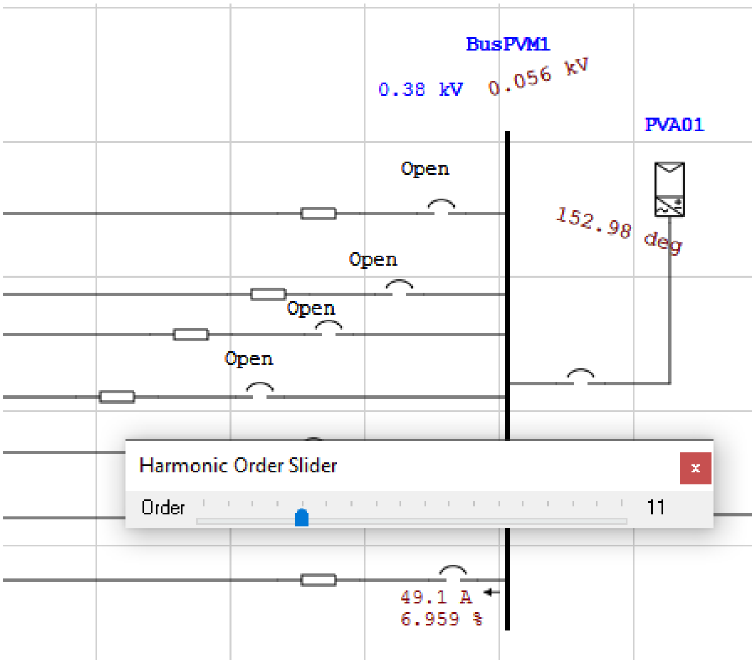


Figure 6.30. Harmonic order slider with harmonic current order.

Other values that can be taken by analyzing the power flow are the current power factor's value, the required power factor, and load in MVA.

After clicking on size filter, then substitute, the filter values are set as shown in Figure 6.31, and it is able to reduce its harmonic order distortion.

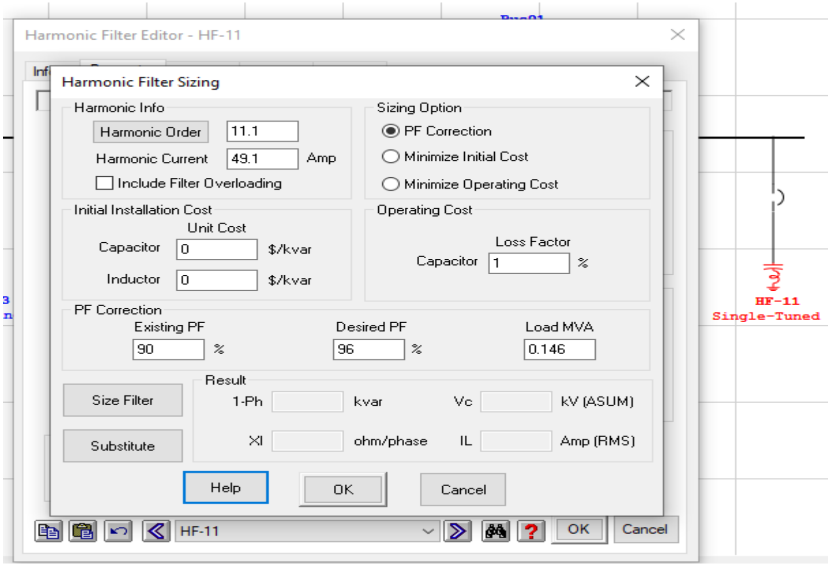


Figure 6.31. SLF setting by ETAP program.

Figure 6.32 shows the difference before and after the injection of the filter, it is clear that THD reduced from 37.15% to 29.7% after adding harmonic filter.

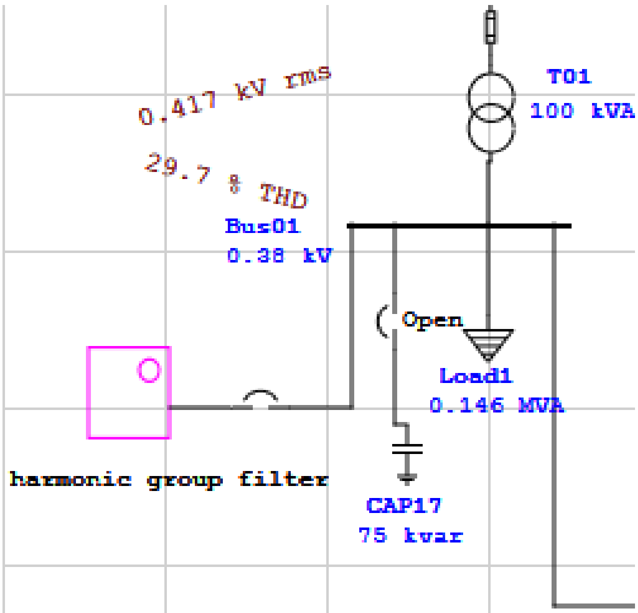


Figure 6.32. Reduced THD by the installation of SLF filter.

The harmonics analysis was repeated to compare the improvement in the shape of the wave and magnitude of THD. Figure 6.33 shows the wave shape after filters injection in the network case study as wave shape was improved.

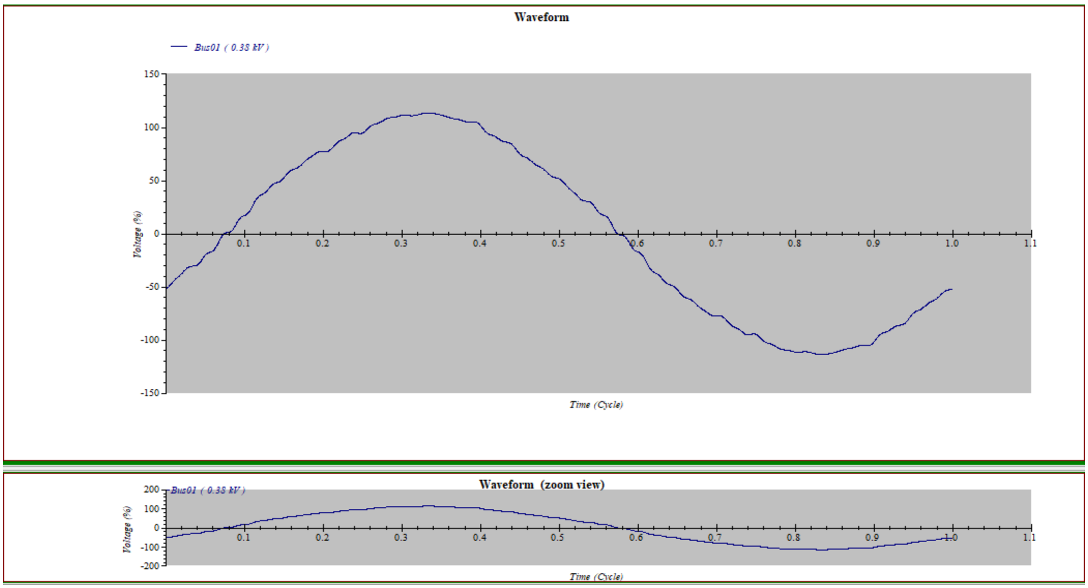


Figure 6.33. Waveform after improvement by SLF injection filters.

Harmonic Load Flow Analysis Alert View - Output Report: Untitled

Study Case: HA
Configuration: Normal
Data Revision: Base
Date: 22-10-2022

Zone Filter Area Filter Region Filter

Critical

Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic
BusPVM1	Bus THD	Exceeds Limit	5	5.15	102.97	Total

Marginal

Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic
BusPVM1	Bus IHD	Exceeds Limit	1.5	2.23	148.76	5.00
BusPVM1	Bus IHD	Exceeds Limit	1.5	1.94	129.39	19.00
Bus52	Bus IHD	Exceeds Limit	1.5	2.3	153.1	5.00
Bus52	Bus THD	Exceeds Limit	2.5	3.01	120.21	Total
Bus01	Bus IHD	Exceeds Limit	1.5	2.3	153.1	5.00
Bus01	Bus THD	Exceeds Limit	2.5	3.01	120.21	Total

Figure 6.34. Marginal alert after adding SLF harmonic filters.

By comparing with Table (6.6) which shows the permissible limit of harmonics, it was found that THD is 3.01% which is an acceptable value for harmonics depending on (IEEE 519).

6.4. SIMULATION RESULT AND DISCUSSION

After analyzing the power flow on the distribution network for both cases that are before and after penetrating the PV distribution generators, where the first scenario is without any injection to know the basic voltage values for each element and the values of the real power and reactive power losses, voltage level for all buses and the capacity load on the feeder. Accordingly, comparing them with the deviation values that will occur in the basic values of the system after the penetration of the PV distribution generation.

6.4.1. Reducing Power Losses

After penetrating the PV distribution generators (1-2) MW and conducting a power flow analysis, it found that PV systems played a major part in absorbing the value and reducing the real power and reactive power losses, as it was proven that the size of photovoltaic distribution generators plays a very important role in reducing losses. It was spotted that the greater the size of PV distribution generation, the greater the reductions in overall network losses. Figures from 6.35 to 6.38 presented the reduced power losses in transformers and total real and reactive power.

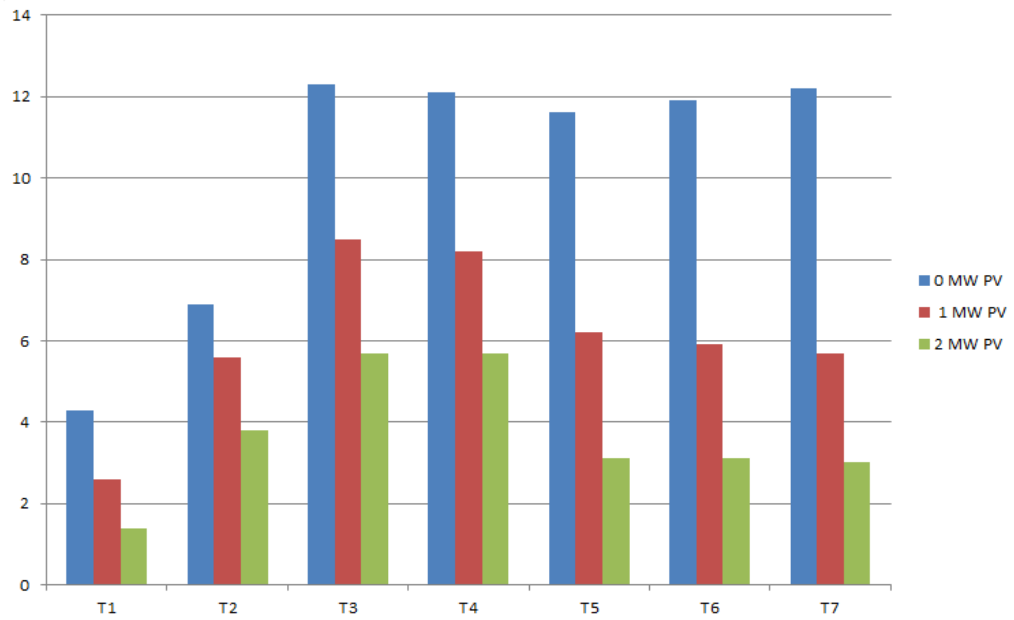


Figure 6.35. Reduction of power losses (kW) after PV penetration into DN for transformers (1-7).

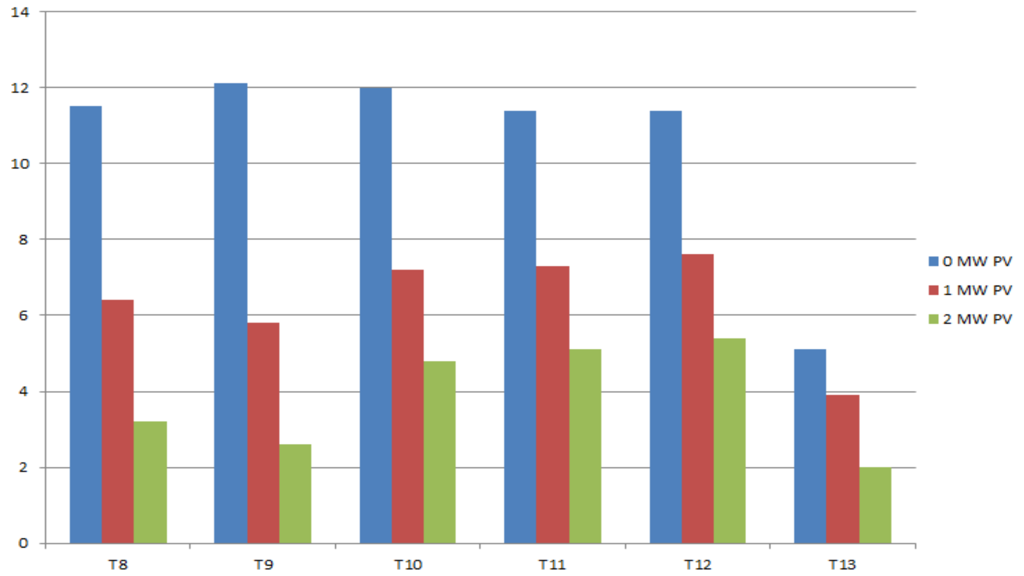


Figure 6.36. Reduction of power losses (kW) after PV penetration into DN for transformers (8-13).

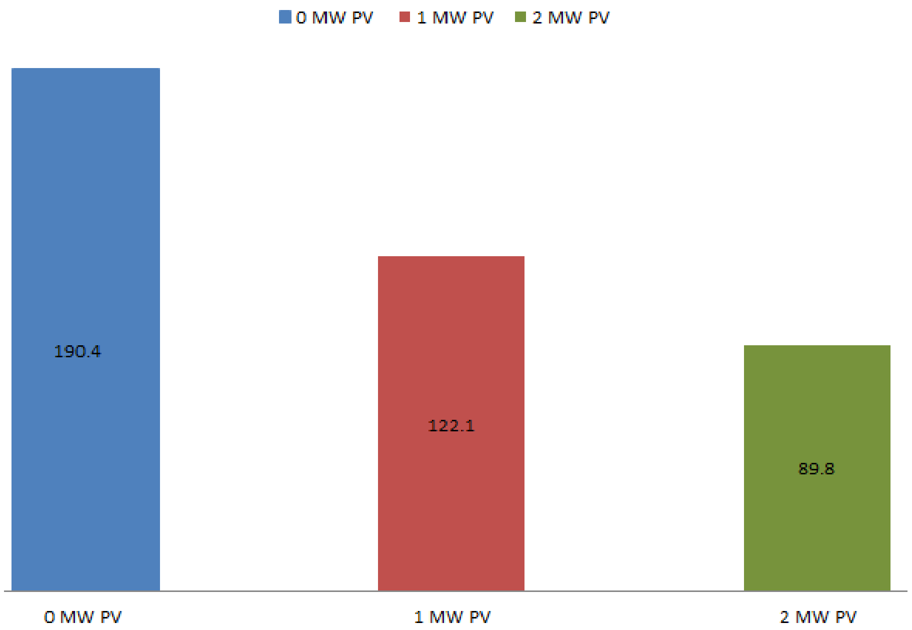


Figure 6.37. Total active power losses (kW) in DN.

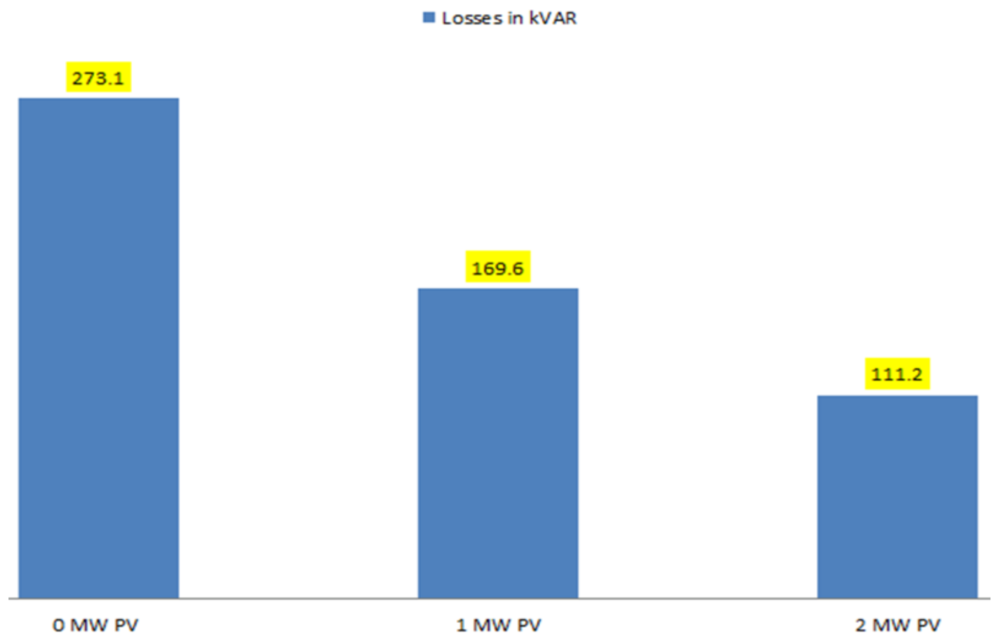


Figure 6.38. Total reactive power losses (kVAR) in DN.

6.4.2. Enhancement of Voltage Drop Percentage

Improving the voltage level of distribution networks is one of the benefits of penetrating distribution generators as the result is reducing drop of voltage in network elements. The size of photovoltaic system also plays the role of a slight improvement in reducing the voltage drop, that is, the greater the size of the photovoltaic system, the less drop of voltage and the improvement of the network voltage.

Figures 6.39 and 6.40 presented the network voltage drop after PV penetration for the buses (1-7) and (8-13), respectively. Figure 6.41 shows the total voltage drop in 11 kV transmission line of the network.

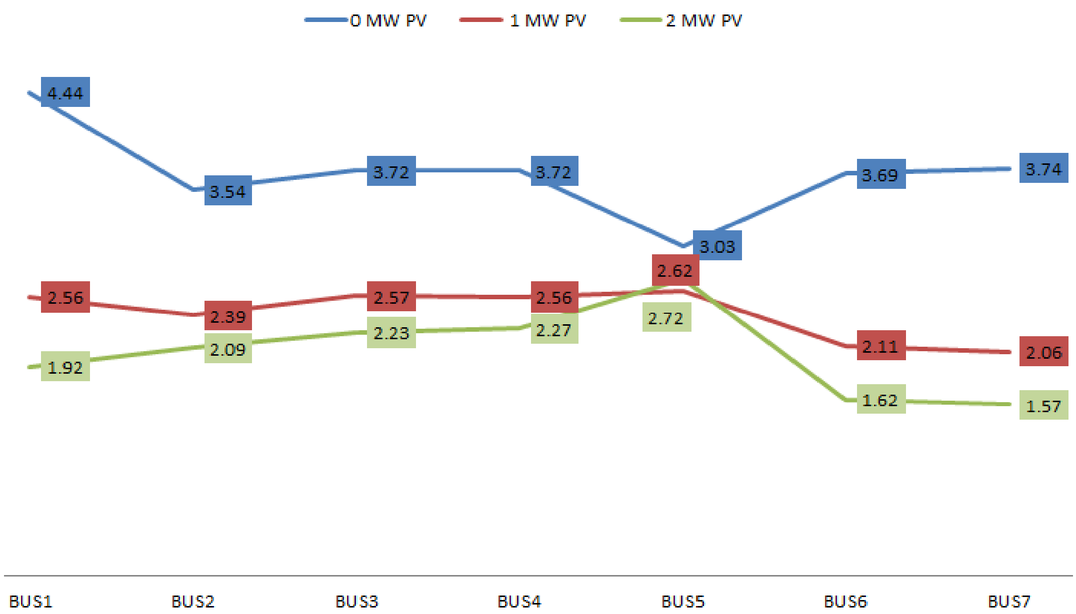


Figure 6.39. Voltage drop (%) after PV penetration into DN for Buses (1-7).

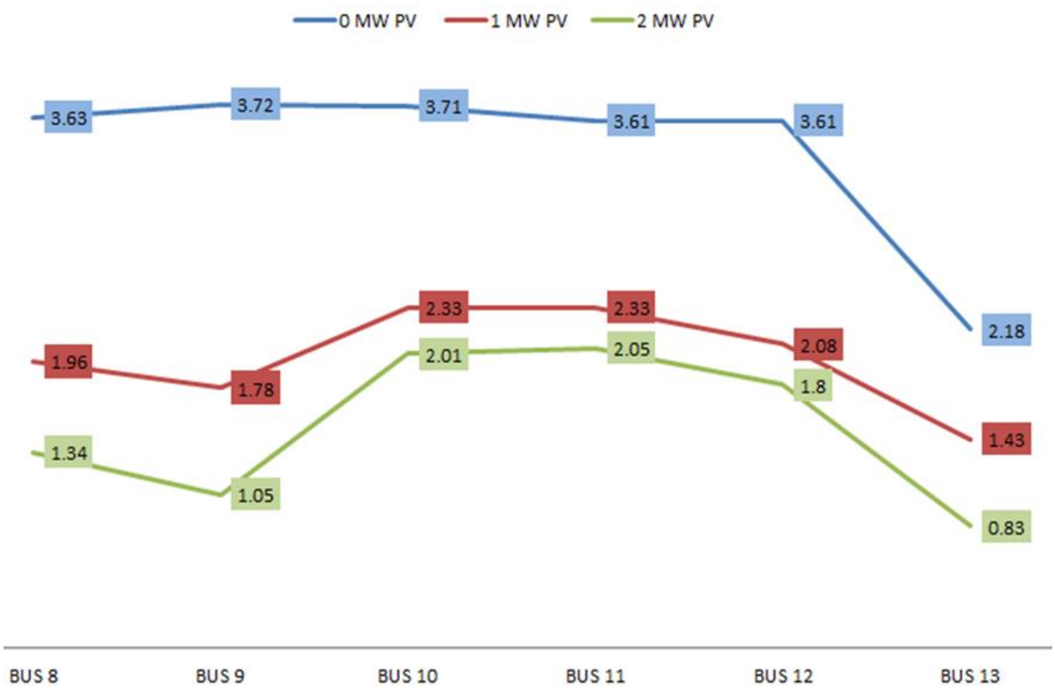


Figure 6.40. Voltage drop (%) after PV penetration into DN for Buses (8-13).

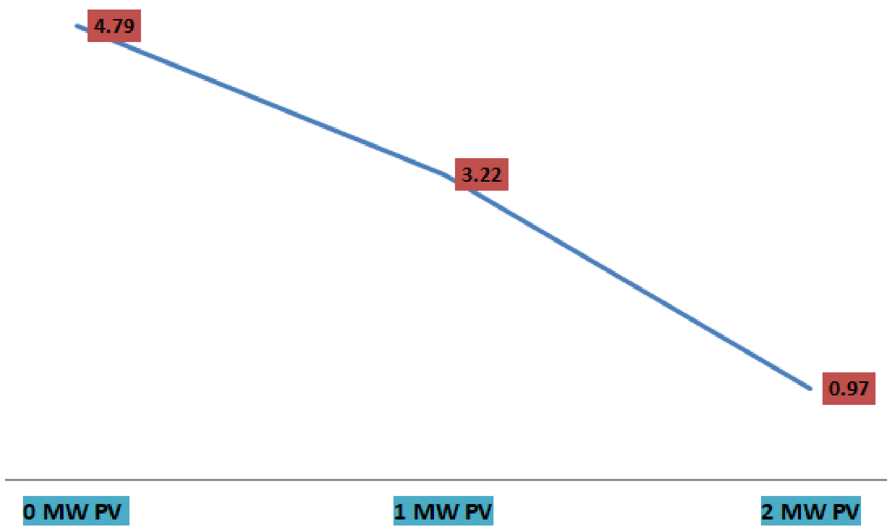


Figure 6.41. The total voltage drop (%) in 11 kV transmission line.

6.4.3. Increase Apparent Power

Unquestionably reducing the active power and reactive power losses leads to an increase in the apparent power. Figures 6.42 and 6.43 shows the apparent power capacity increase seen in all buses of the distribution network.

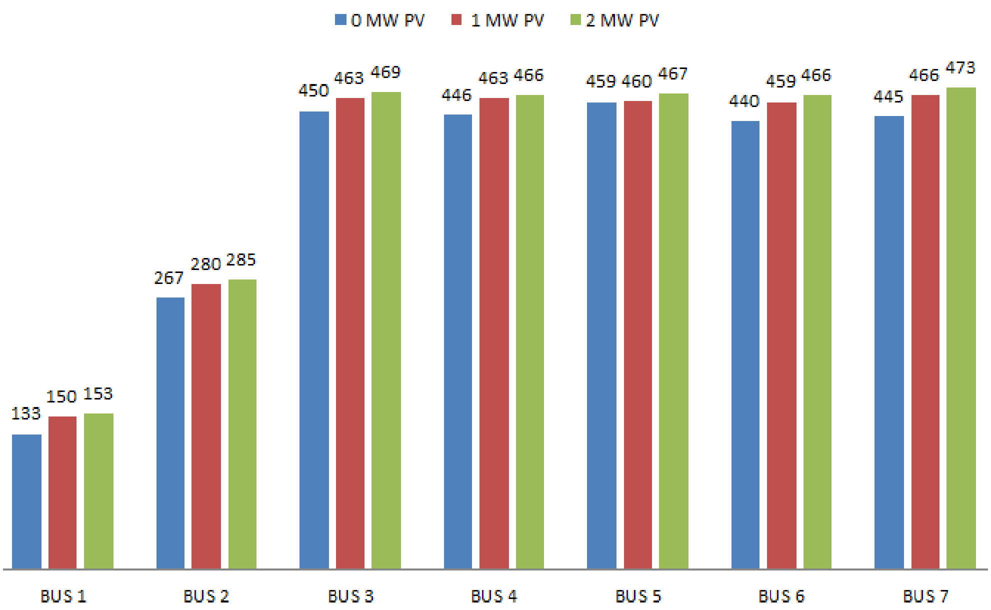


Figure 6.42. Apparent power in kVA for BUS (1-7).

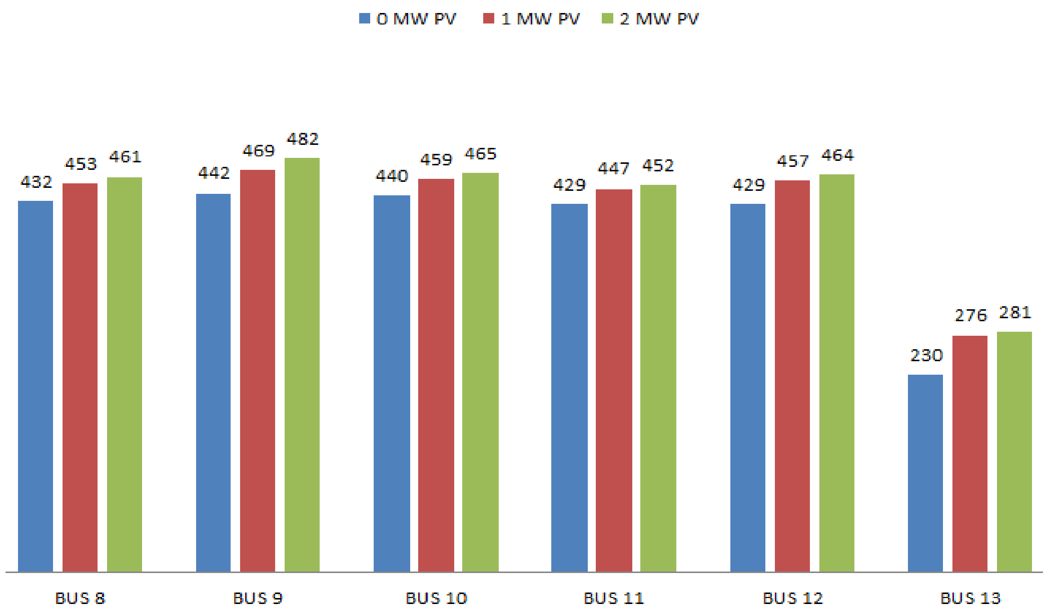


Figure 6.43. Apparent power in kVA for BUS (8-13).

6.4.4. Reduce Feeder Load

One of the distribution generators' benefits is to decrease the loads on the main grid. Figure 6.44 proves the increase in the penetration capacity of the distribution generators decreases the loads on the feeder to the network case study and reduces dependence on the main grid.

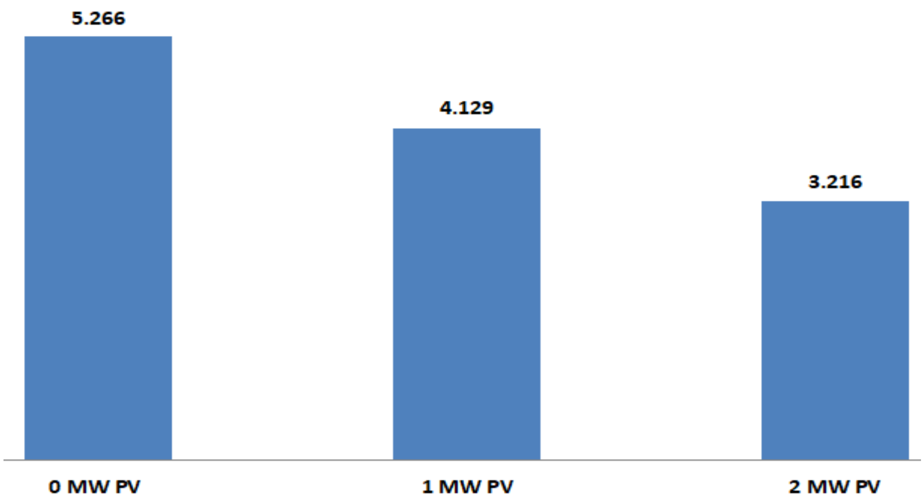


Figure 6.44. Feeder load (MVA) before and after PV penetration.

6.4.5. Harmonic Simulation Result

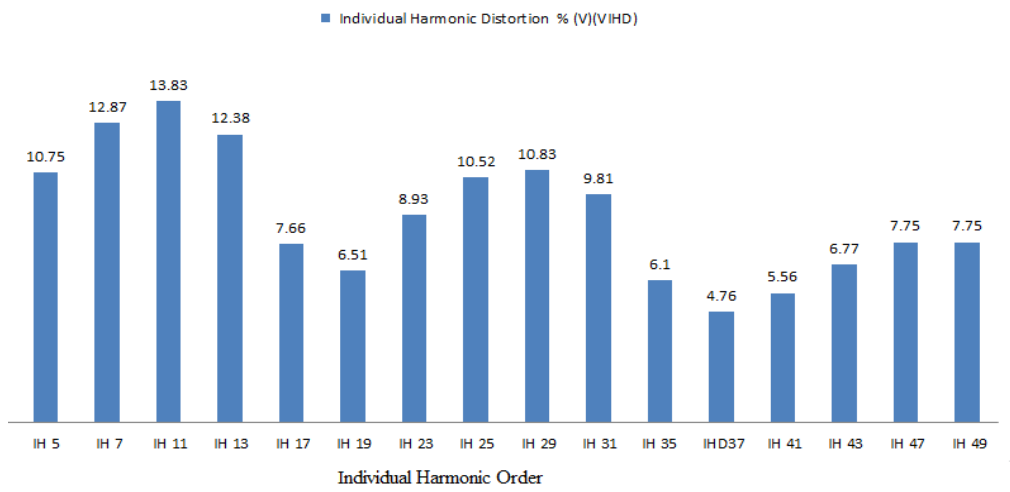


Figure 6.45. Individual harmonic distortions (%) before adding harmonic filter to Bus 1.

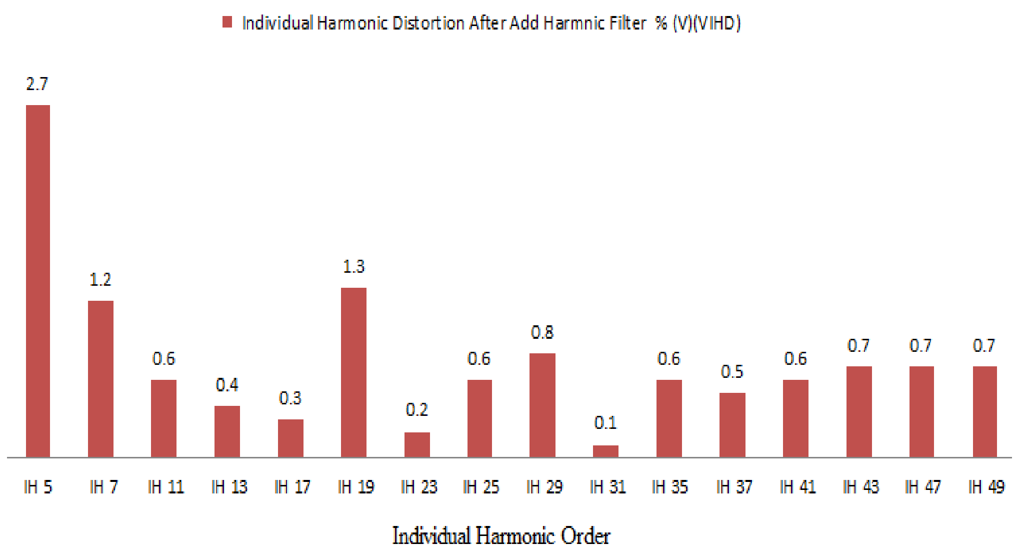


Figure 6.46. Individual harmonic distortion (%) after adding harmonic filter to Bus 1.

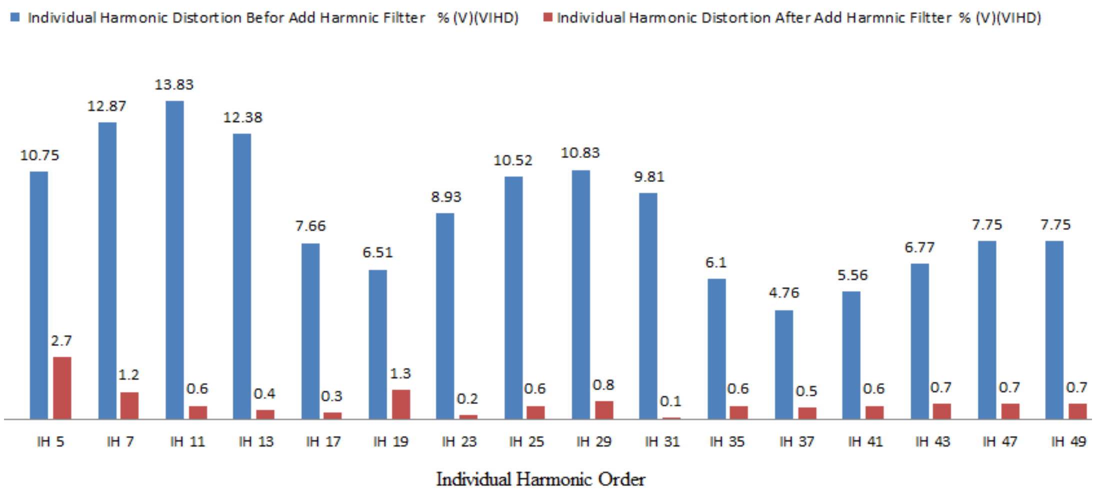


Figure 6.47. Comparing VIHD before and after adding harmonic filter to Bus01

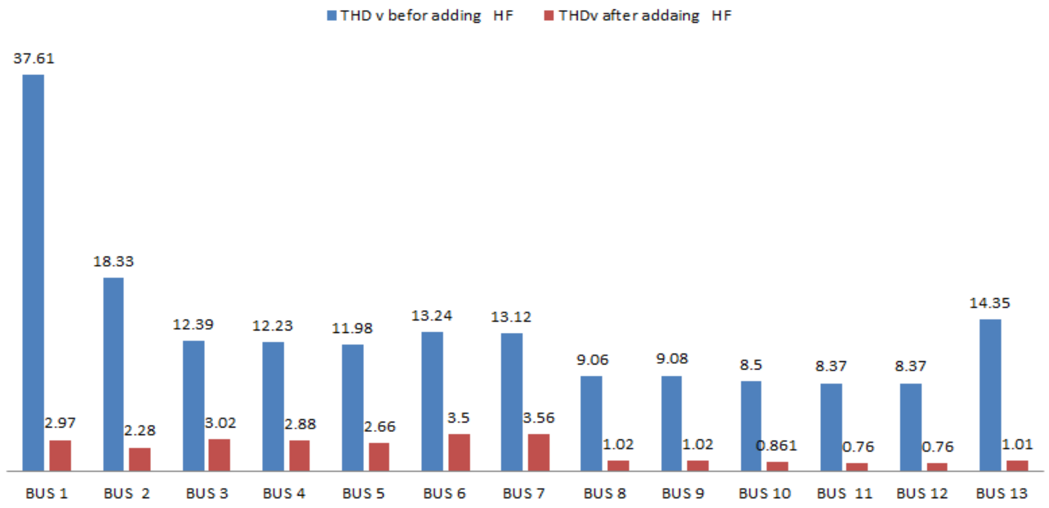


Figure 6.48. Comparing THD before and after adding harmonic filter to all DN.

PART 7

CONCLUSION AND FUTURE RECOMMENDATION

The participation of renewable energy, represented by photovoltaic, in power systems contributes significantly to improving distribution networks because of their benefits in reducing active power and reactive power losses, improving voltage, besides reducing the load on main feeder. It contributes a major role in the development of establishing reliable power systems for the consumer and increases the participation of renewable energy, and also reducing dependence on traditional power systems that require large transmission networks and less reliability for the consumer. All these issues are present in the electrical power system in Iraq, choosing a case study from one of the Iraqi cities then improving its distribution network, through the use of solar energy as in injection. This work supports reducing the issues and losses suffered by the energy sector in Iraq and it was done by analyzing the network power flow of the study case, showing the possibility of linking and penetrating renewable energy with a positive effect on distribution network reduces consumers' dependence on private generators, which causes financial losses, the emission of gases harmful to the environment, as well as the damage they cause to distribution networks as a result of an arbitrary connection. On the flip side, there are some disadvantages represented by the increase in harmonics resulting from electronic devices, which requires the design of filters to reduce harmonics and improve the quality of power.

This work can be developed in the future through the following recommendations:

1. Adding sources of electrical energy storage such as batteries to compensate for the shortage that occurs during the absence of solar energy and to ensure the continued participation of energy distribution in improving the energy system.

2. It is possible to study the economic and environmental aspects of using solar energy in distribution networks to consumers instead of diesel generators and compare its economic feasibility and the impact of pollution instead of private generators.

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RESUME

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