An-Najah National University
Faculty of Graduate Studies

THE IMPACTS AND MITIGATION STRATEGIES OF REVERSE POWER FLOW IN DISTRIBUTION ELECTRICAL NETWORK WITH HIGH PENETRATION OF RENEWABLE ENERGY SYSTEMS

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Dedication

Praise be to Allah, Lord of the worlds

To the spirit of our Prophet Mohammad (Blessings and Peace upon him)

I dedicate this research work to my beloved family, whose support, and love encourage me throughout this journey and inspire me to follow my dreams.

To my parents, who instilled in me the values of perseverance and hard work. Thank you for teaching me that my job in life was to learn, to be happy, and to know and understand myself; only then could I know and understand others. Thank you for guiding me as a person, violinist, and teacher and offering editing expertise throughout this process.

I am especially grateful to my husband,Hashem Herzallah, who supported me emotionally and financially, thank you for listening, offering me advice, and supporting me through this entire. I always knew that you believed in me and wanted the best for me. Thanks for the support you provided during this journey. Your companionship made the tough times bearable.

My children(Mustafa, Masa, and Sanad) are my little angels, who inspired and still inspire me to follow my dreams. Who stands by me through every challenge, I hope you get the best in your life, my little heroes.

To all my colleagues and friends, thank you for your thoughts, well-wishes.

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Declaration

I, the undersigned, declare that I submitted the thesis entitled:

THE IMPACTS AND MITIGATION STRATEGIES OF REVERSE POWER FLOW IN DISTRIBUTION ELECTRICAL NETWORK WITH HIGH PENETRATION OF RENEWABLE ENERGY SYSTEMS

I declare that the work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's Name: تسنيم عبدالكريم خليفة

Signature:

Date: ١٥/١٠/٢٠٢٤م

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THE IMPACTS AND MITIGATION STRATEGIES OF REVERSE POWER FLOW IN DISTRIBUTION ELECTRICAL NETWORK WITH HIGH PENETRATION OF RENEWABLE ENERGY SYSTEMS

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Abstract

The increasing penetration of renewable energy systems (RES), particularly distributed generation (DG) such as solar photovoltaic (PV), has transformed modern power distribution networks. While this technology offers environmental and economic benefits, it also introduces significant technical challenges. One of the most critical issues is reverse power flow (RPF), which occurs when the generation from distributed sources exceeds local demand, causing power to flow back toward the electrical distribution network.

This thesis addresses the impacts of reverse power flow due to high penetration in the electrical distribution network; A detailed analysis is conducted to assess how RPF affects voltage profiles and transformer losses. Through ETAP simulated an electrical distribution with 33 buses, 14 step-down transformers with 10KV /0.38KV rating and 19 loads connected to the buses. The network simulation was done by adding a solar PV energy system and addressing the benefits, then increasing the number of solar PV arrays connected to buses to reach PV penetration at various levels of 20%,40%,60%, in PV penetration no existing to reverse power flow, the buses' voltages rising to an acceptable levels and this effect improves the electrical network and reduces the transformers losses,but if any solar PV arrays connected to a bus and generated power exceeds the demand load that connected to that bus a reverse power flows towards the distribution transformer causing losses and rising in voltage.

The network was simulated by reducing the load demand to reach PV penetration levels of 109%, and190%,the reverse power flow amounts was increased with the increase in PV penetration to high levels.and this case occurred when the solar PV system generated power in peak times while the load demand is light,high level of PV penetration produced many impacts as voltage rising issue and transformers losses issue.various mitigation strategies were proposed as BESS (battery energy storage system), load shifting,and zero export devices and smart inverters. Assessment was done for each mitigation strategy and choosing between these solutions depends on the specific grid conditions, regulatory framework, and available financial resources.

Keywords: Reverse power flow (RPF), Distributed generation (DG), Solar PV system, High level of PV penetration, Impacts of reverse power flow, Voltage rising,Transformers losses, Mitigation strategies, Load shifting, BESS (battery energy storage system), Zero export, Smart inverters.

Chapter One

Introduction

1.1 Background

With the increasing of electricity demand, there's a need for more power plans. However, traditional power plants have some challenges like carbon emissions, high transmission losses, and increasing the costs of construction. They're also less reliable, because of this, and the push for more renewable energy sources, Distributed Generation (DG) has become more common, especially with grid-connected Photovoltaic (PV) systems.

Distributed Generation (DG) brings a lot of benefits, such as making the grid more reliable, enhancing efficiency, and cutting down on carbon emissions, but these advantages also change how we manage, and protect the grid.

While Distributed generation offers many of positives, it also introduces challenges, particularly with power flow in electrical distribution networks due to the high penetration of renewable systems, to manage these issues, various strategies have been explored as smart inverters, energy storage solutions, and demand side management. These strategies are developed to mitigate reverse power flow issues, and ensure the grid continues to function smoothly.

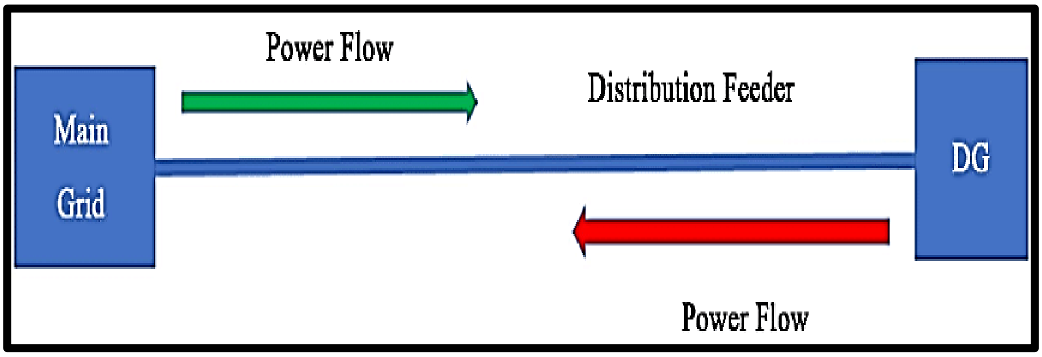
1.2 Problem Statement

The increasing integration of renewable energy systems(RES) in electrical distribution networks has transformed the dynamics of power flow within these systems, while renewable energy sources (RES), such as solar photovoltaic (PV), offer environmental and economic benefits; their decentralized nature introduces new challenges to the operation of traditional power plants. One of the most critical challenges is the occurrence of Reverse Power Flow (RPF).

Reverse Power Flow (RPF) is a phenomenon that occurs in electrical distribution networks when the amount of power generated by renewable resources exceeds the local electricity demand. This excess power flows back into the electrical distribution network instead of being consumed locally. On the other hand, RPF could also be a result of the reduction in the local load demand to the point of excess power in the networks which then flows backward. RPF is dangerous in the distribution networks as it leads in the distribution of electrical networks, and also critically affects the sensitivity and parameters of protective device coordination, hence negatively affecting power quality [1].

Figure 1.1

Reverse Power Concept



This thesis investigates the impacts of reverse power flow on distribution networks and explores various mitigation strategies to ensure stable and efficient operation. The study combines theoretical analysis, and case studies to provide a comprehensive understanding of the problem and propose practical solutions. Figure 1.1 [2] illustrates the concept of reverse power flow, where generated power from distributed sources exceeds local demand, causing power to flow back toward the electrical distribution network.

1.3 Research Objectives

The primary objective of this thesis is to comprehensively assess the impacts of reverse power flow in distribution electrical networks with the high penetration of Renewable Energy Systems (RES) and to propose and evaluate effective mitigation strategies. To achieve this overarching goal, the research is guided by the following specific objectives:

1. To analyze the impacts of (RPF): investigate the impacts of reverse power flow in distribution networks, including voltage rise, protection coordination issues, and the economic implications of reverse power flow, including the need for costly infrastructure upgrades and the potential for disrupted tariff structures, cannot be overlooked. This analysis will identify the key factors that contribute to these impacts and quantify their effects under varying levels of RES penetration.
2. To assess the economic implications of reverse power flow: Examine the economic impacts associated with reverse power flow, such as the costs of necessary network upgrades, maintenance, and modifications to existing tariff structures. The objective is

to evaluate the financial burden on distribution network operators, utilities, and consumers, and to explore the economic viability of distributed generation in the occurrence of reverse power flow.

3. To evaluate the environmental impacts of Reverse Power Flow: Analyze the broader environmental, and social implications of reverse power flow, including its effects on grid reliability, stability, and public perception of renewable energy systems.
4. To assess existing mitigation strategies: Conduct a critical review of mitigation strategies for reverse power flow, including grid infrastructure enhancements, advanced grid management techniques, and technological innovations. The objective is to assess the feasibility, and limitations of these strategies in managing reverse power flow in high-penetration RES scenarios.
5. To provide recommendations for sustainable renewable energy system integration: Based on the results of the simulation analyses, develop recommendations that support the sustainable integration of RES into distribution networks. These recommendations will focus on effective management of reverse power flow.

1.4 Research Methodology

This thesis is designed to investigate the impacts of reverse power flow in electrical distribution networks with high penetration levels of renewable energy systems (RES), to evaluate some mitigation strategies. Furthermore, the methodology includes evaluating the network’s PV hosting capacity, which determines the maximum level of PV generation that can be integrated without exceeding operational constraints, performance indices are calculated to quantify the network’s response to PV integration, including metrics for reverse power flow impact.

A comprehensive literature review will be conducted to gather previous knowledge on the (RPF), the high renewable energy sources penetration, and the mitigation strategies of reverse power flow. This review will:

1. Examine previous research papers to understand the state of knowledge.
2. Identify the technical and economic challenges of reverse power flow (RPF) in electrical distribution networks.

1.4.1 Theoretical Analysis

Theoretical analysis will be developed to understand the concepts and mechanisms of reverse power flow. This analysis will include:

1. A detailed exploration of power flow equations and their application to distribution networks with high RES penetration.
2. Analysis of the technical impacts of reverse power flow, such as voltage rise, network component overloading, and protection system malfunctions.
3. Examination of economic implications, including costs associated with network upgrades and modifications to tariff structures.

1.4.2 Simulation Modeling

Simulation models will be created to quantitatively assess the impacts of reverse power flow and evaluate the effectiveness of various mitigation strategies. The steps involved include:

Selection of appropriate simulation tools, such as ETAP (Electrical Transient and Analysis Program). Analysis capabilities offered by ETAP are extensive and include motor starting analysis load flow analysis short circuit analysis stability analysis and more. This enables thorough analysis and power system optimization by engineers.

1. Development of a base model representing a typical distribution network with varying levels of RES penetration.
2. Simulation of different scenarios, including varying levels of RES penetration, load conditions, and network configurations.
3. Implementation of different mitigation strategies in the simulation models to evaluate their effectiveness in managing reverse power flow.

1.4.3 Case Study

Case study will be used to validate the results from the theoretical analysis and simulations. The case study will involve:

1. Selection of an electrical distribution network with renewable energy resources (RES) such as solar energy systems, and collection data including power flow measurements, network configurations, and operational records.

2. Analyzing data of this network, and studying the high penetration case and its impacts including voltage regulation, transformer losses and protection coordination.
3. Implementation of reverse power flow mitigation strategies on this network and assess these strategies.

1.5 Structure of the Thesis

This thesis is structured to explore and discuss the impacts and mitigation strategies of reverse power flow (RPF) in distribution electrical networks with high penetration of renewable energy systems, it is outlined as follows:

Chapter 1: delves an introduction to the topic of the thesis, outlining the problem, research objectives, scope of this study, and literature review that introduces the phenomenon of reverse power flow (RPF), outlines the challenges it presents to distribution networks, and reviews the existing literature on reverse power flow and its impacts on distribution networks. It explores key studies on distributed generation (DG) technologies, grid integration challenges, and solutions proposed for managing RPF. Various technical and economic aspects of high renewable energy penetration are also examined.

Chapter 2: Impacts of Reverse Power Flow on Distribution Networks; This chapter focuses on the technical challenges posed by RPF in distribution networks as voltage rise issue, transformer losses, the impact of RPF on traditional protection mechanisms and relay coordination in addition to the economic impact. And Mitigation Strategies for Reverse Power Flow; This chapter discusses various mitigating strategies to eliminate the effects of RPF, including: load shifting and demand response, battery energy storage systems (BESS),and smart inverters.

Chapter 3: Case Studies and Simulations; This chapter presents simulation results and case studies by ETAP, demonstrating the impacts of RPF on an electrical distribution network. Various scenarios are simulated to: Analyze and quantify voltage rise and transformer losses under different load and RPF conditions. Evaluate the effectiveness of various mitigation strategies in improving network performance. And the economic feasibility; This chapter synthesizes the findings from the simulations, case studies, and literature review. The economic feasibility of the proposed mitigation strategies is discussed.

Chapter 4: Conclusion; Presents a discussion of the results. This chapter provides an opportunity to analyze and interpret the data gathered from the research, discussing the findings and their implications. The chapter concludes with recommendations for future research and potential applications of the findings in practical settings.

1. 6 Literature Review

1.6.1 Renewable energy systems (RES)

Technologies known as renewable energy systems (RES) use natural processes to produce energy in a sustainable way. These technologies use renewable energy sources like solar and wind power which are continuously and naturally renewed. These systems are essential for lowering greenhouse gas emissions and advancing environmental sustainability. Energy security and reducing climate change are becoming more and more important to the international community. Installing RES has emerged as a key tactic in contemporary energy policies. When used properly renewable technologies minimize secondary waste production and have a positive environmental impact. They meet present as well as future social and economic demands making them sustainable. Energy originates from the sun. Its two main forms are light and heat. The environment absorbs and changes these solar energy sources in a number of ways. Wind and biomass energy are examples of renewable energy flows that result from some of these changes. When renewable energy technologies replace traditional energy sources there is a significant chance to lower greenhouse gas emissions and slow down global warming. [3].

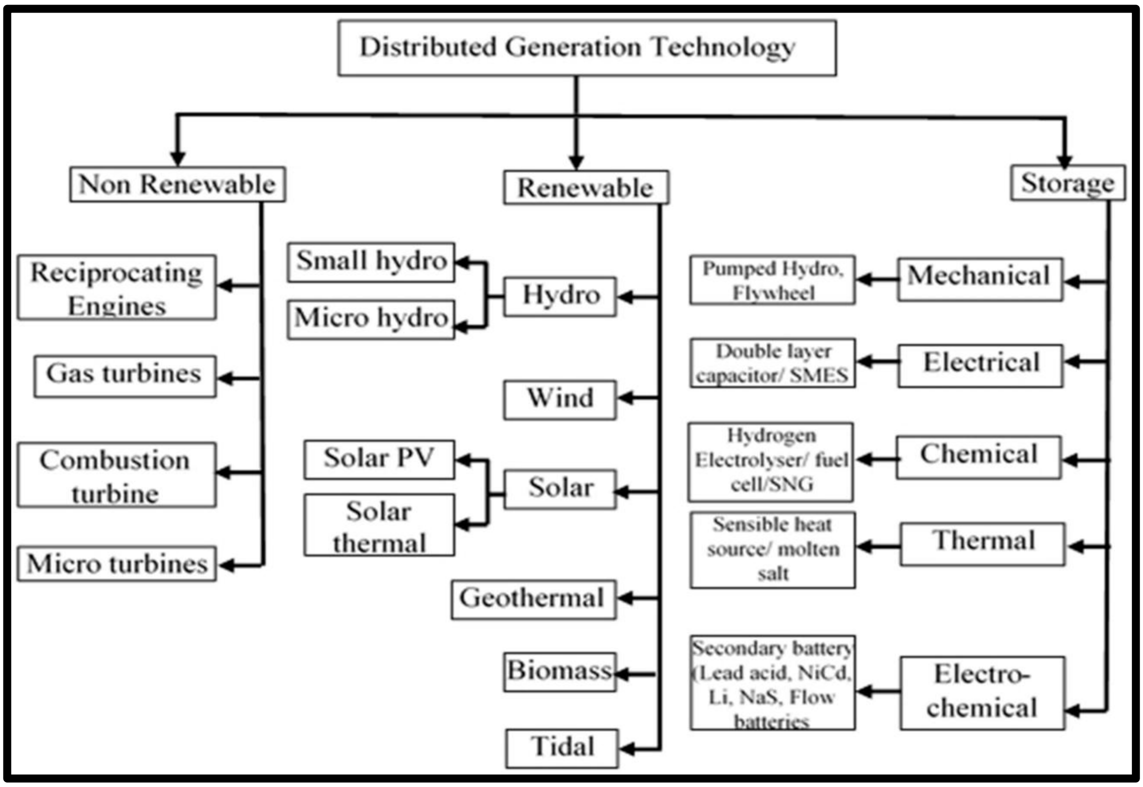
RES can be categorized based on the natural resources they harness; there are main types of renewable energy, solar energy, wind energy, geothermal energy, hydropower and biofuels. But the most popular one is Solar Energy especially in our region.

1.6.2 Distributed Generation (DG)

In order to help with the supply of electricity distributed generators (DG) are small generators that can be installed in low-voltage or medium-voltage distribution networks. Moreover distributed generation (DG) is a small-scale power generation technology that is connected to the loads of consumers via a power utility's distribution network to supply electricity at a location that is closer to the customers than a central station. [4].

Figure 1.2

Distributed Generation Technology



The thesis will focus on solar photovoltaic systems as a distributed generator (DG) plays a significant role in the context of reverse power flow in distribution networks.

Figure 1.2 [5] depicts different types of distributed generation (DG) technologies that contribute to renewable energy integration in distribution networks. These technologies play a significant role in understanding the impacts of reverse power flow.

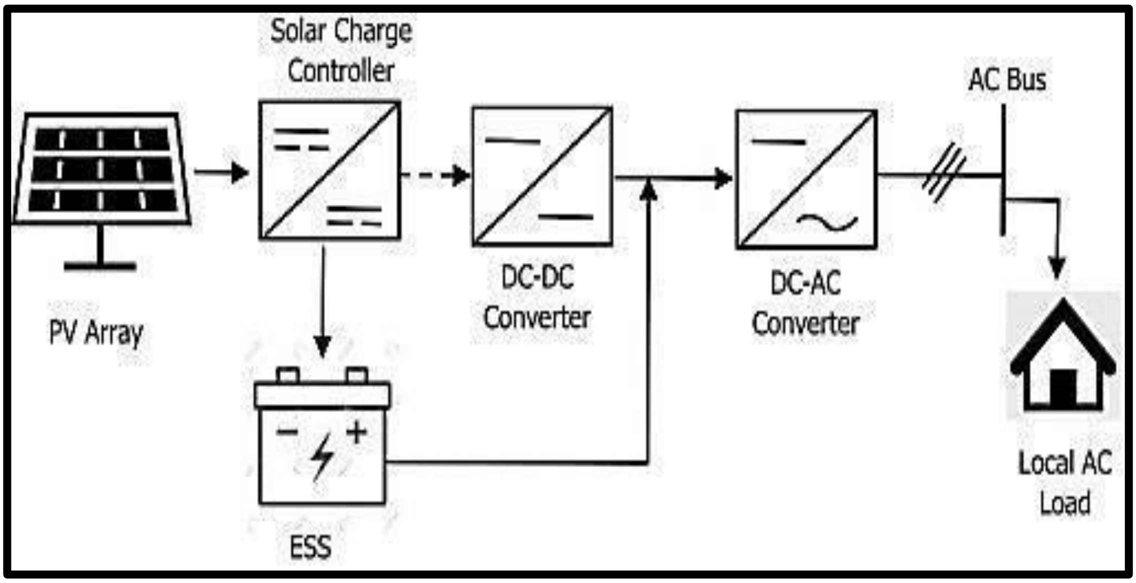
Solar PV system as a DG in the electrical distribution network:

The photovoltaic system, often referred to as a PV system or solar power system, is an electrical energy system designed to harness usable solar power through photovoltaic cells. It includes several components, such as solar panels that capture and convert sunlight into electricity, a solar inverter that changes the output from direct current to alternating current, along with mounting structures, cables, and other electrical accessories necessary to set up a functioning system. Many large-scale photovoltaic systems utilize tracking systems to follow the sun's daily movement across the sky, producing more electricity than fixed systems [5].

The main components of PV system are PV modules, convertors, inverters, storage, charge controller, and cables. As shown in figure 1.3 [6]. However, the desired efficiency of PV systems relies on many factors as well as understanding the component functionality and configuration. There are different types of PV systems, namely grid-connected, standalone, and hybrid PV systems.

Figure 1.3

PV solar system



Applications of a photovoltaic system

Today, among the various renewable energy technologies available, photovoltaic energy is one of the fastest-growing options. With the significant reduction in the cost of manufacturing solar panels, it is set to play a crucial role in renewable energy generation. Typically, these panels have a lifespan of about 25-30 years and are used in a variety of applications:

1. Utility-scale applications: The alternating current generated by the inverter can be used to power household appliances and machinery. Excess electricity can also be sold to the grid through a net-metering system. Photovoltaic systems are often paired with storage systems, typically battery storage, which can provide energy during peak periods.
2. Solar rooftops: Solar rooftop adoption is on the rise due to its numerous benefits, such as cost-effectiveness, secure investment, government support, and carbon footprint reduction.

3. Off-grid systems: Off-grid systems avoid reliance on grid connections and utilities, utilizing the solar energy generated directly. Battery storage can be used during low sunlight hours or at night. In some cases, conventional generators may serve as backups.

1.6.3 Reverse Power Flow Concepts

One of the significant impacts due to high penetration of the distributed generators (DG) is the phenomenon of reverse power flow, which generally occurs when the generation of a distributed electric power plant exceeds the local load demand, causing power to flow in the opposite direction to normal power flow.

Causes of Reverse Power Flow are

1. Distributed Generation(DG): Despite the installation of DG(e.g., solar PV systems) provides several benefits to the distribution network, improper planning of these devices can have a negative impact on the system's operation, the main impact is generating reverse power flow into the distribution network. When these sources generate more power than needed locally, the excess flows back into the grid. As a result, when installing DG, it is important to determine the best location, the appropriate nominal capacity, as well as the type and number of generators to be installed [7].
2. Energy Storage Systems (ESS): The deployment of energy storage systems, such as batteries, further contributes to reverse power flow. When these systems discharge stored energy back into the grid during periods of high electricity prices or low demand, they can induce reverse flow, depending on the timing of their operation. Research by [8] highlights the role of ESS in both mitigating and exacerbating reverse power flow, depending on the timing of their operation.
3. Load Variation and Demand Response: During times of low demand, even small amounts of distributed generation can cause reverse power flow. For example Load variation with Solar PV systems has many parameters to evaluate the PV influence on the grid. The sizing, peak power of the PV system and the rated power of the grid are important Parameters, all of them related to the PV penetration level.

Conversely high-level penetration presents a number of difficulties such as voltage rise and fluctuation reverse power flow that exceeds transformer and cable ratings higher power losses and problems with protective equipment. Impact assessment studies must be completed prior to the network’s acceptance of PV energy resources. With a highly accurate high impact assessment of PV generation in the electrical network however it is possible to integrate the amount of PV energy into the distribution network while maintaining technical and operational constraints on the electrical system.

1.6.4 PV Penetration levels

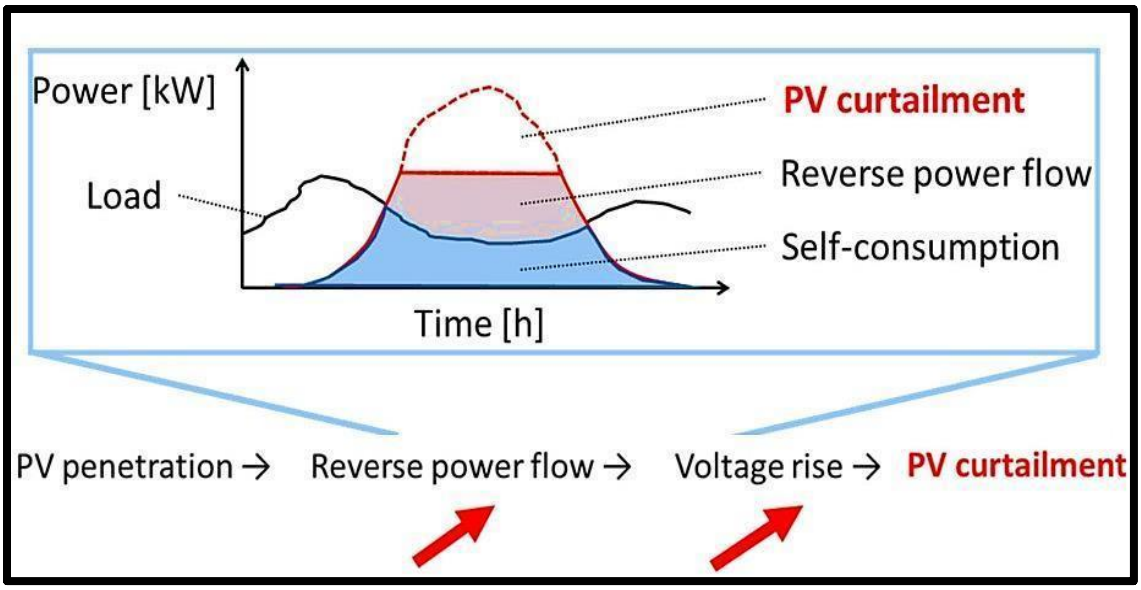
Determining penetration levels is a primary goal of impact assessment investigations and is contingent upon the assessment criteria. Since it depends on a number of variables including the feeders electrical characteristics and the location of the PV systems it is challenging to determine the maximum allowed penetration level that can be installed on the feeder. Since the maximum allowed penetration levels that can be installed on the feeder depend on a number of variables including the electrical characteristics of the feeders and the location of the PV system it is challenging to determine these limits. may be compromised leading to improper operation. Unfortunately, if network upgrades are not implemented high penetration levels may have a detrimental effect on the network and cause reverse flow.

Depending on the depth of PV penetration RPF (reverse power flow) can form in different parts of the distribution network. Additionally unidirectional voltage regulators are vulnerable to failure when exposed to RPF as a result the substation load tap changers may regulate with an increase in voltage which could cause line drop compensators to operate incorrectly. A 25% PV penetration rate is known to increase reverse power flow which results in nuisance tripping. Components of distribution systems are known to be vulnerable to overloading due to other protection concerns.

Specifically, RPF is demonstrated to align with feeder terminals and often lead to overloading of transformers and transmission lines. The loading level will gradually drop as more PV systems are injected into the feeder. But if penetration increases even more the power flow is reversed overloading the feeder in the end. Reverse power flow (RPF) can occur as a result of high penetration levels without network upgrades. Consequently, reverse power flow a phenomenon that arises when solar PV generates more grid power than the load demand is caused by high penetration numbers. As a result, depending on the PV systems size and location the grids power flow may be reversed. [1].

Figure 1.4

Concept of PV penetration



For instance, during off-peak hours, the reduced load combined with constant DG output may result in reverse power flow. Figure 1.4 [9] shows the concept of PV penetration in a distribution network. The percentage of PV generation relative to the total load is shown, with higher penetration levels indicating greater influence on the power flow and potential reverse power flow scenarios.

1.6.5 Impacts of RPF on Distribution Networks

The integration of renewable energy systems (RES), such as solar photovoltaic (PV) systems, has led to the increasing occurrence of reverse power flow in electrical distribution networks. Reverse power flow (RPF), where electricity flows from the distribution network back to the transmission network or generation sources, presents critical impacts on the operation and stability of the electrical systems. The literature reveals that these impacts are particularly pronounced in areas with high penetration of renewable energy systems, leading to several significant impacts in voltage regulation, power quality, and protection devices performance.

1. Voltage Regulation Issues

One of the most significant impacts of reverse power flow (RPF) is the challenge it poses to voltage regulation in distribution networks; traditional distribution networks are designed for unidirectional power flow, with voltage levels typically decreasing as the distance from the substation increases. However, when reverse power flow occurs, the excess power generated by DG causes an increase in voltage levels, particularly at the points where this power is injected into the network. In [8] The author conducted both steady-state and dynamic analyses under different loading scenarios and the results show that as solar PV penetration increases voltage increases to unacceptably high levels. This is especially noticeable when there are low load conditions and a high penetration of solar PV. In order to address the problem of voltage rise during solar PV penetration in a typical distribution network that supplies residential customers a hybrid active power curtailment–reactive power injection control technique is covered.

Figure 1.5

Voltage variation under different PV penetration levels in a distribution network

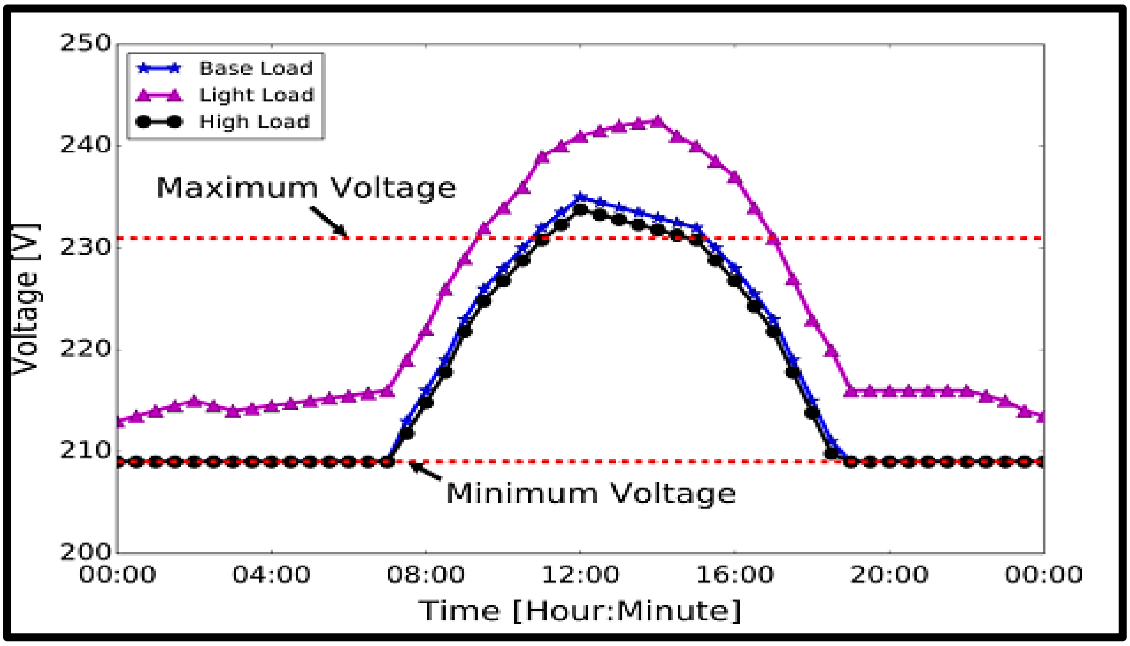


Figure 1.5 [8] illustrates how voltage levels in a distribution network vary with different load demands when integrated with PV systems. Higher loads typically lower voltage, while lighter loads, especially with PV generation, can cause voltage rise.

Figure 1.6

Voltage variation for different solar PV penetration conditions in electrical distribution network

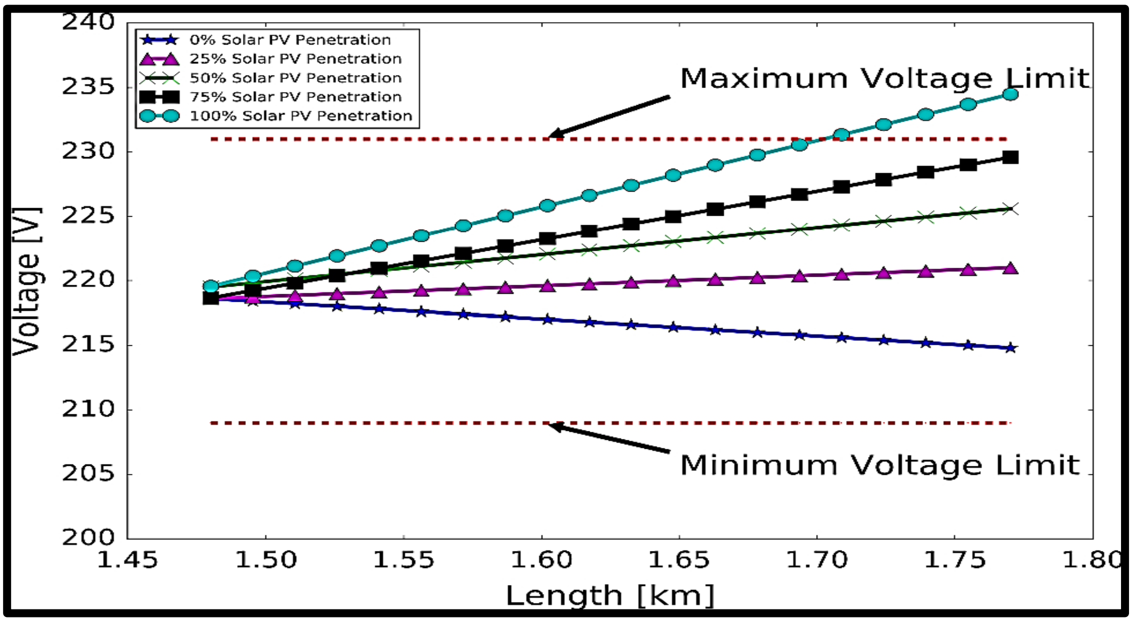


Figure 1.6 [8] demonstrates the impact of different levels of PV penetration on voltage variation within the distribution network. As penetration increases, voltage levels rise, highlighting the challenge of maintaining stable voltage under high renewable energy integration. Studies such as those by [8] have shown that this voltage rise can exceed the operational limits, leading to potential overvoltage conditions that may damage consumer equipment and grid infrastructure. The problem is exacerbated in networks with long feeder lines and low load density, common in rural or suburban areas with significant DG penetration. Voltage regulation devices, such as on-load tap changers (OLTCs), capacitor banks, and voltage regulators, may not operate correctly under these conditions, as they are typically designed to manage voltage drops, not rises. Consequently, reverse power flow can necessitate the deployment of advanced voltage control strategies, including dynamic voltage regulation and the use of smart inverters with reactive power support capabilities.

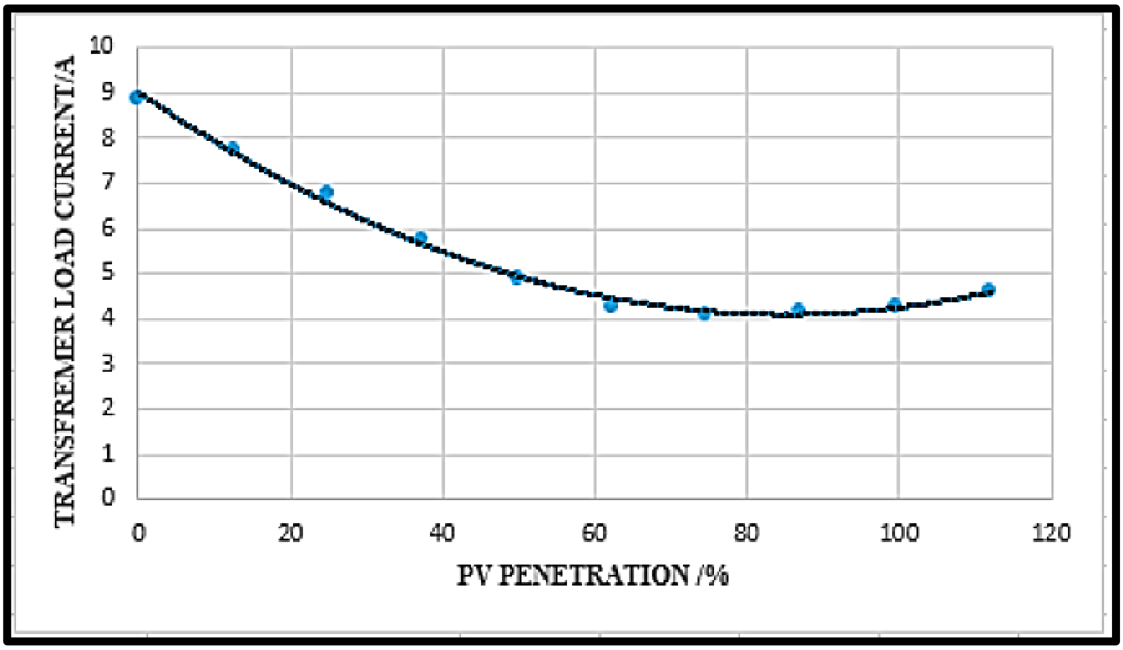
2. Losses in distributed transformers

The transformers capacity is freed up when photovoltaic (PV) energy initially penetrates the system and lowers the load current. However the load current starts to increase as penetration rises and reverse power flow (RPF) occurs. If PV penetration increases steadily the load current may surpass the transformers full load rating and cause damage.

Distribution transformers should not be overloaded when operating continuously. Its lifespan may be shortened by overloading the transformer. Nevertheless the transformer may overheat in certain situations due to harmonics. This implies that harmonic loads in the network can raise currents and raise transformer temperatures even in the absence of overloading. When solar PV enters the LV network reverse power enters the substation transformer overloading it above its rated capacity. Therefore in order to avoid transformer overload cases caused by reverse power flow increased penetration must be kept to a minimum [9].Also if the reverse power flow is not restricted, then the interconnect transformer loses its life by 25%.

Figure 1.7

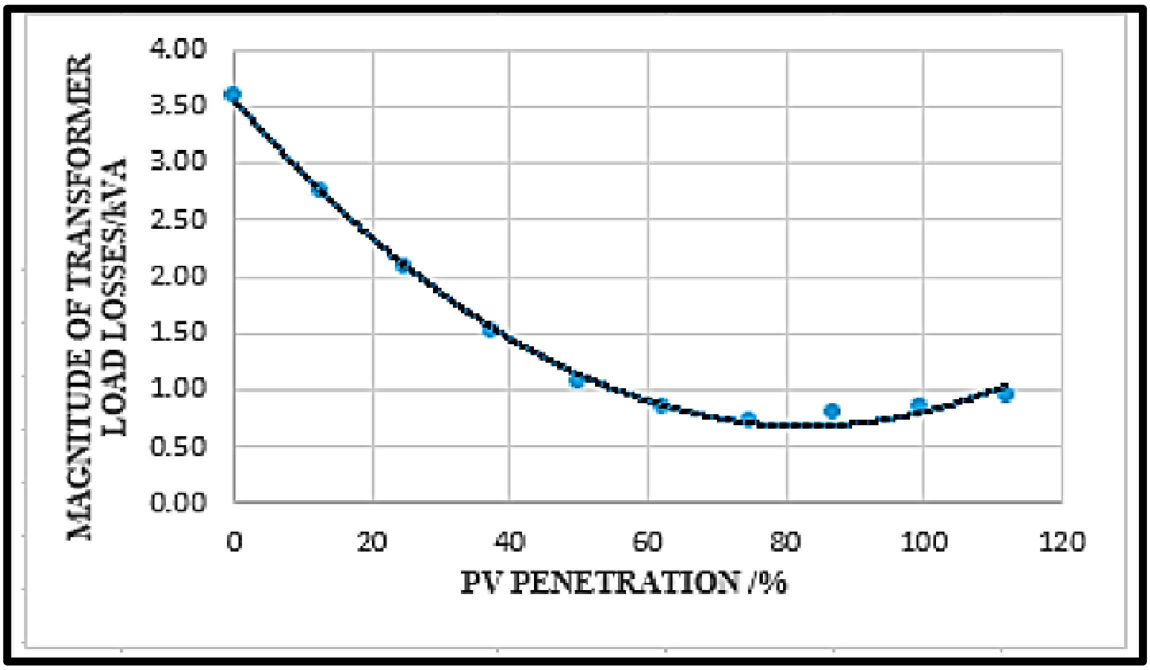
Transformer Percentage Loading VS. PV penetration



In figure 1.7 [3] transformer loads must meet the demands of current loads and account for future load growth in the distribution system. As the penetration of photovoltaic (PV) solar energy increases, capacity is initially freed up, which reduces the loading ratio on the substation transformer.

Figure 1.8

Transformer load losses VS. PV penetration



AS shown in figure 1.8 [3], PV penetrations effect on system losses is demonstrated by the fact that as PV penetration rises the size of transformer load losses falls. Increases in PV generation free up grid capacity which lowers transformer losses. The transformer may overload when the PV generation surpasses the local demand and RPF takes place before then. Increased active and reactive currents in overloaded transformers lead to greater load losses. But the losses begin to rise after 88–30% penetration. Researchers propose using a variety of control energy storage schemes to store excess PV production during periods of peak load in order to reduce these losses.

3. Power Quality Concerns

The degree of stability dependability and consistency of electrical power is referred to as power quality. It is crucial because any departure from the anticipated power quality levels may result in unfavorable outcomes like data loss system shutdown and equipment damage or malfunction. The negative effects of reverse power flow on distribution networks power quality will be covered in this thesis. In certain situations, power quality problems like power factor and current harmonics have been found. However, as PV generators become more widely installed on the grid the systems overall power quality may begin to suffer. As PV penetration increases the main power quality problems that could occur are power factor reverse power flow power system stability and security voltage variation (sag and swell) and harmonics [10].

These power quality issues will result in false tripping of barkers, blackouts, introducing harmonic distortion, voltage fluctuations, frequency deviations, overheating of transformers and neutral conductors, increasing the power loss in the power system, damaging the sensitive electronic components, and capacitor banks. It is mandatory that these power quality issues should be restricted as per IEEE and IEC standards for the smooth and secured operation of the grid.

Research by [11] states that at higher penetration levels, there are various negative impacts on the grid. Parameters such as voltage magnitudes and current harmonics are affected beyond the specified margins. Thus there is a need for research to analyze the system for its optimal penetration level or enhancing the level of penetration on the grid using Flexible AC Transmission System (FACT) Controllers & Devices without affecting the power quality standards as per the IEEE or IEC code and maintaining the system stability.

Furthermore, reverse power flow can introduce challenges in maintaining frequency stability. In scenarios where DGs contribute a substantial portion of the total generation, the grid's ability to regulate frequency can be compromised, particularly during periods of low demand when reverse power flow is most likely to occur. This instability necessitates the integration of more sophisticated control systems that can dynamically adjust generation and load to maintain power quality.

4. Protection System Challenges

The occurrence of reverse power flow complicates the operation of protection systems in distribution networks. Traditional protection systems are designed under the assumption of unidirectional power flow, where faults and overcurrent conditions can be easily detected and isolated based on predictable flow patterns. However, reverse power flow (RPF) disrupts these patterns, leading to discoordination of protection devices.

Studies conducted by [11] discussed that short-circuit analysis reveals an increase in fault currents at the failing node because two or more sources will feed the fault. In this case, the first source is the grid equivalent, and the second is the distributed generator, which will contribute its maximum short-circuit power. As a result, the sensitivity of protection coordination is affected by the inclusion of distributed generators. This is because the current levels during reverse power flow may not trigger relays correctly.

Reverse power flow can affect on the performance of protection relays, overcurrent protection relays, calibrated based on the expected direction and magnitude of flow, may fail to operate during reverse flow conditions, allowing faults to persist longer than under normal conditions, this delay in detecting the fault increases the risk of equipment damage and reduces the reliability of the electrical distribution network.

5. Impact on Grid Stability

The impact of reverse power flow (RPF) on the stability of the electrical grid is another area of concern, particularly as electrical distribution networks become more decentralized with the integration of renewable energy sources (RES). Reverse power flow (RPF) can introduce new behaviors in the grid, affecting its ability to respond to disturbances and maintain stable operation. Research by [12] investigates that the unpredictability of reverse power flow (RPF), combined with the variable nature of renewable energy generation, can make it challenging for grid operators to maintain a balanced system. The traditional methods of grid balancing may no longer be sufficient, requiring control systems that can manage the flow of power across the network.

Furthermore, the presence of reverse power flow (RPF) can affect the coordination between transmission and distribution systems, especially in scenarios where large-scale distributed generators (DGs) are feeding power back into the transmission lines. [12]noted that this interaction could lead to unintended consequences, such as the overloading of transmission lines or transformers, threatening grid stability.

1.6.6 Existing Mitigation Strategies for Reverse Power Flow

In [14], the author also analyzed the impact of RPF due to high distributed generator (DG) penetration on a selected distribution network. The study shows that higher DG penetration leads to greater reverse power flow (RPF). During high DG generation, transformers in the DG system require more reactive power to transfer large amounts of active power. This is combined with DG units operating at a constant power factor in a capacitive/leading mode (absorbing reactive power), thus requiring the DG system to absorb more reactive power from the grid. Conversely, during low DG generation, the system requires less reactive power, and the excess reactive power in the DG system (resulting from cable charging effects and lower reactive power absorption by the distribution network) flows back into the grid.

Many researchers have proposed solutions to eliminate reverse power flow in distribution networks. In [15], appropriate voltage and reactive power requirements were suggested, and short-circuit studies were recommended before implementing DG in the distribution system. DG systems should provide reactive power compensation, such as installing capacitor banks, reactors, Static VAr Compensators (SVC), or Static Synchronous Compensators (STATCOM), to balance the reactive power in the DG system. This helps prevent unnecessary reactive power absorption (or generation) from (or to) the grid. In [15], the authors proposed an online method using a dynamic venin equivalent to prevent overvoltage control issues in micro-grids with photovoltaic (PV) systems, as the overvoltage resulted from RPF, limiting the output of PV systems. In Sudhakar et al., (2018), the authors evaluated using EV batteries as storage devices for home PV systems to reduce RPF and lower EV dependence on the grid for charging. The study considered electricity demand forecasts as well as solar irradiation, showing that electricity bills could be reduced by controlling RPF in the network. In Judge et al., (2022), the authors proposed the use of reverse power relays to mitigate reverse power flow in the distribution network due to DGs. The reverse power relay monitors power flow from central generation units and disconnects DGs in the distribution network when reverse power is detected. In [16], an impedance-based technique was proposed to monitor and detect RPF in a high-penetration PV distribution network. Testing this technique on an IEEE 34-node test feeder demonstrated its ability to detect minor variations in PV penetration levels, as well as the rapid transient effect of cloud movement on PV output. In [17], the use of a high-penetration PV system based on smart inverters was suggested to enhance design efficiency and energy output.

Chapter Two

The Impacts and the Mitigation Strategies of Reverse Power Flow

2.1 Impacts of Reverse Power Flow on Distribution Network

2.1.1 Voltage Rise Issues

In the context of renewable energy, penetration refers to the proportion of electricity generated from renewable sources relative to the total electricity generated. This percentage shows how much of the electricity supply comes from renewable resources.

It is calculated by dividing the electricity generated from renewable sources by the total electricity generated (including all sources), then multiplying by 100. For example, if a country generates 1,000 tWh (terawatt-hours) of electricity in a year and 300 tWh comes from renewable, the renewable penetration rate is 30%.

Renewable distributed generation is becoming more and more integrated into power systems which has both advantages and disadvantages. With RES integration into a power system the occurrence of undervoltage at the far end of a traditional electrical distribution network might no longer be a cause for concern. At the Point of Common Coupling (PCC) between RES and the distribution network however issues like voltage rise or overvoltage and reverse power flows could arise if RESs are integrated into the power system. The effects of the voltage rise effect and the reverse power flow constraint in power systems with a high concentration of renewable energy sources are discussed in this thesis. In short DGs like photovoltaic systems can raise voltages throughout the distribution network when they inject power into the grid particularly when there is little load. This occurs as a result of power flowing through the distribution system in reverse when generated power exceeds local load demand. Reverse power flow or RPF can result in problems with voltage regulation in the distribution network. This means that RPF can raise voltage levels above acceptable bounds and impact the functionality of equipment and devices that are connected.

Analysis of voltage rise phenomena in electrical power networks with high penetration of renewable distributed generations.

The simplified voltage rise equation:

$$\Delta V = P \cdot R + Q \cdot X \tag{2.1}$$

Can be expanded by including per-unit system values, line impedance components, and more precise network characteristics.

Detailed Voltage Rise in Per-Unit (P.U.) System:

In per-unit terms, the voltage rise can be expressed as:

$$\Delta V_{pu} = \frac{P_{pu} \cdot R_{pu} + Q_{pu} \cdot X_{pu}}{V_{nom}} \tag{2.2}$$

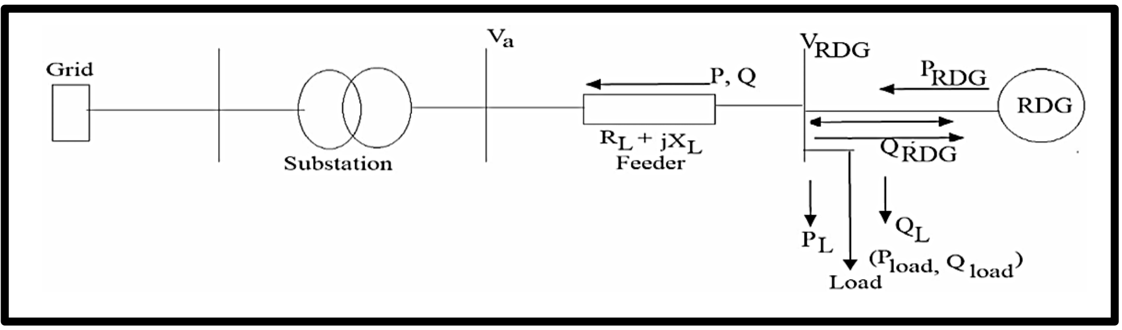
Where:

ΔV_{pu}= Voltage rise in per-unit
P_{pu}=Active power flow in per-unit
Q_{pu} = Reactive power flow in per-unit
R_{pu}= Line resistance in per-unit
X_{pu} = Line reactance in per-unit
V_{nom} = Nominal voltage level (typically 1 P.U.)

In this equation, the term (Ppu.Rpu) represents the resistive component of voltage rise, while (Qpu.Xpu) represents the reactive component of voltage rise.

Figure 2.1

RDG integration to distribution network



Despite the increasing number of Renewable Distribution Generators (RDGs) and their penetration levels there are critical challenges such as voltage rise issues.

Refer to figure 2.1 [18], the rise in voltage at the Point of Common Coupling (PCC) due to the RDG integration can be expressed in (2.3).

$$\Delta V = V_{RGD} - V_a \approx \frac{RP+XQ}{V_{RDG}} \tag{2.3}$$

Where P = (P_{RDG} $-P_L$) and Q = ($-Q_L$ $\pm Q_{RDG}$).

From (2.3) V_{RDG} can be expressed in terms of per unit in (2.4).

$$\Delta V = V_{RDG} - V_a = R(P_{RDG} - P_L) + X(-Q_L \pm Q_{RDG}) \tag{2.4}$$

While the loads are consuming the active power (PL) and reactive power (QL) RDG typically exports active power (+PG) to the grid and reactive power (±QG) to or from the grid. While reactive power may be exported or absorbed based on the RDGs excitation scheme settings such as synchronous generators used for wind energy conversion and induction generators that require reactive power to run some RDGs that are integrated into the distribution network export real power to the grid when the loads connected to the system fall below the generator output. Real power is exported to the grid by solar photovoltaic systems at a predefined power factor the direction of power flow depends on the systems real and reactive power loading in relation to the generators output and system losses. If the most critical scenario is one in which the load demanded with a peak RDG generation is reduced this scenario can be analyzed using (2.4) and then re-expressed in (2.5). The (2.6) is valid in the meantime if the network is running at unity power factor. This presumption allows the (2.4) to be re-expressed in (2.7).

$$P_L = 0,\ Q_L = 0, \text{ and } P_{RDG} = P_{RDGMax} \tag{2.5}$$

$$\pm Q_{RDG} = 0 \tag{2.6}$$

$$\Delta V\ Critical = V_{RDGmax} - V_a \approx RP_{RDGmax} \tag{2.7}$$

As can be seen from (2.7) the penetration power of the RDG and the distribution lines resistance (R) both affect the voltage increase. Thus if the distribution lines resistance stays constant the (2.7) can be re-expressed as (2.8). From (2.8) it can be inferred that the voltage in a distribution network with RDG penetration is directly proportional to the active power that the RDGs inject into the network.

$$\Delta V\ Critical \propto P_{RDGmax} \tag{2.8}$$

1. Case #1: PV Penetration - with PV generation 524kW at peak period and variable load

This section investigates the impact of reverse power flow due to high penetration of Renewable Energy Resources (RES) on a distribution network. A Solar PV of 524 kW is integrated into the network as shown in Figure 2.2 to meet a certain load with peak load 1MVA while the distribution substation voltage is controlled at 100%. Tables 2.1 and 2.2 depict the measured voltage rise percentage verse the PV penetration percentage at Bus#3, which calculated as follows:

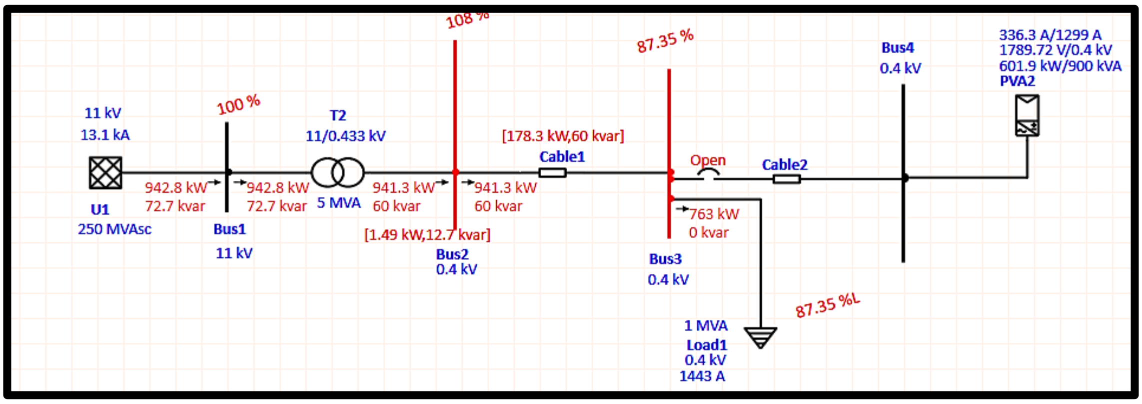
$$\text{PV penetration level} = \frac{\text{PV generation}}{\text{overall system load}} * 100\% \, P_{RDGmax} \qquad (2.9)$$

In this case, reverse power flow occurred at light Load less than 0.5 MW and the voltage rises to unacceptable limits. Each following figure investigates a different situation for a PV solar system. Figure 2.2 showed that the circuit breaker is open, which means no power generated from PV system. In figure B.1 in appendix B the PV solar system connected to bus#4, generates 524.1 kW goes to the load with rated apparent power of 1 MVA, the voltage at bus #3 rises from 87.35 % to 97.76%.In other hand, in figure B.2 in appendix B the voltage continues rising due to reduction in demand load, but still there is no reverse power flow since the PV generation doesn’t exceed the load demand.

As shown in figures B.3, B.4, B.5 in appendix B both amounts of reverse power flow, and the voltage rise increase with high PV penetration, caused by reduction in load, while PV generation is about 524 kW.

Figure 2.2

Simple electrical network with not- connected solar PV



Note. Circuit breaker is open, the PV solar array isn’t connected.

Figure B.1 in appendix B demonstrates a basic network setup where a solar PV system is connected to a 1 MVA load. The impact of PV generation on network voltage levels rising as PV power is integrated. In the setup in figure B.2 in appendix B, the load is reduced to 0.8 MVA, causing a further voltage increase due to the lower demand relative to PV generation. This illustrates the effect of reduced load on voltage rise, further more as shown in figure B.3 in appendix B, the load is further decreased to 0.4 MVA, resulting in a more significant voltage rise as the PV system generates power that exceeds local demand, approaching conditions for reverse power flow. Also figure B.4,and figure B.5 in appendix B show that the voltage's rise issue at an even lower load of 0.3 MVA and 0.2 MVA, where the excess generation from the PV system significantly raises voltage, posing challenges for network stability.

Table 2.1 shows the impacts that occurred at Bus #3 -(PV solar system generation at peak period is about 0.524 MW,and the demand load varies from 1 MVA to 0.2 MVA).

Table 2.1

Reverse power flow with different load demand

The load	Generation PV/ load demand	Voltage V%	The amount or reverse power flow
1 MVA -C.B is open	0	87.35%	0
1 MVA- C.B is closed	50%	97.76%	0
0.8 MVA	60%	101.3%	0
0.4 MVA –light load	130%	109.2%	45.9kW
0.3MVA- light load	170%	111.4%	146.8kW
0.2MVA- light load	200%	113.7%	252.3kW

The flow chart in figure B.6 in appendix B highlights how RPF contributes to this voltage rise at specific points in the network, emphasizing the challenge of maintaining voltage rising under high PV penetration levels.

2. Case# 2: PV Penetration – with variable PV generation and 1MVA peak load

In this case the load demand is constant and PV power generation is varied. Figure B.8 in appendix B, illustrates reverse power flow in a distribution network, which is about 295.2 kW flows back to the grid, and the voltage rises to unacceptable limit 114.6%,causing losses in cable 1 and the transformer.

Referring to figure 2.2, and figures B.1, B.7 and B.8 in appendix B, Table 2.2 is produced, and it explains that distributed generation power exceeds load demand, causing energy to flow back towards the substation, which impacts transformer loading and voltage regulation.

Table 2.2

PV Penetration - with PV generation (variable) and load constant

The load (constant)-1MVA-	PV generation (variable)-(generation PV/load demand)	Voltage V%	The amount or reverse power flow
1 MVA -C.B is open	524 kW -0%	87.35%	0
1 MVA- C.B is closed	524kW-50 %	97.76%	0
1 MVA- C.B is closed	1048kW-92%	106.4%	0
1 MVA- C.B is closed	1627kW-123%	114.6%	295.2 Kw

As shown in table 2.2 the voltages at bus 3 increased to unacceptable levels due to the presence of reverse power flow 295.2 kW.

2.1.2 Losses in distributed transformers

We can break down the total losses in distribution transformers into three components: copper losses, core losses, and harmonic losses. The equations below illustrate losses under the presence of RPF in distribution networks with high renewable energy penetration levels.

In electrical distribution networks with a high penetration of photovoltaic (PV) systems, reverse power flow can increase losses in cable systems. The losses primarily include resistive losses; which arise from the increased current flowing through cables when power flows back to the grid, dielectric losses; which occur in the insulation material and can be exacerbated by higher voltage, and harmonic losses; introduced by the inverter-based nature of PV systems, harmonics cause additional heating and energy dissipation in cables as higher- order currents generate extra eddy currents and interfere with power quality. As PV penetration level increases, the losses become more pronounced, affecting the efficiency and lifespan of the distribution network’s cables. So to mitigate these losses, measures like improving voltage regulation and applying harmonic filtering could be considered to minimize energy waste.

1. Copper Losses (I²R Losses)

Copper losses are caused by the current flowing through the transformer windings. These losses are proportional to the square of the current and the resistance of the windings. Under reverse power flow conditions, the magnitude of the current can increase, leading to higher losses.

For a given transformer:

$$P_{copper} = {I_{LOAD}}^{2} * R_{W} \tag{2.10}$$

Where:

P_{copper} is the copper loss (in watts),
I_{LOAD} is the current flowing through the windings (in amperes)
R_{W} is the resistance of the windings (in ohms).

Impact of RPF: During RPF, the current through the windings may reverse, but since the losses depend on I^{2}The direction of current doesn't matter, only its magnitude. If RPF increases the current magnitude:

$$P_{RPF} = {I_{RPF}}^{2} * R_{W} \tag{2.11}$$

Where I_{RPF} is the increased current due to RPF. If I_{RPF}>I_{LOAD} copper losses will increase.

2. Core (Iron) Losses

Core losses consist of hysteresis losses and eddy current losses. These are related to the voltage and frequency applied to the transformer and are present as long as the transformer is energized, regardless of the power flow direction.

The total core losses P_{CORE} can be expressed as:

$$P_{CORE} = P_{hysteresis} + P_{eddy} \tag{2.12}$$

Where:

$P_{hysteresis}$ depends on the material properties of the core and the magnetic flux density,
P_{eddy} is proportional to the square of the voltage and frequency.

For reverse power flow conditions:

$$P_{hysteresis} = K_H . B_{MAX} . F \tag{2.13}$$

Where:

K_H is a constant depending on the core material,
B_{MAX} is the peak magnetic flux density,
F is the frequency of the system (usually 50 or 60 Hz).

The eddy current loss can be expressed as:

$$P_{eddy} = K_E . V^2 . F^2 \tag{2.14}$$

Where:

K_E is a constant related to the material and thickness of the core laminations,
V is the voltage applied to the transformer

Impact of RPF: RPF can cause voltage fluctuations. If RPF leads to higher voltage levels, the eddy current losses will increase.

3. Harmonic Losses

Harmonic losses occur due to the presence of higher-order harmonics in the current and voltage waveforms, typically caused by inverter-based DG systems during RPF. Harmonics can increase both copper and core losses.

Harmonic Copper Losses**:** Harmonic currents increase the overall RMS current flowing through the transformer, which further increases copper losses.

4. Total Losses in the Transformer Due to RPF

The total transformer losses during reverse power flow, accounting for copper, core, and harmonic losses, can be expressed as:

$$P_{total,\,RPF} = P_{copper,\,RPF} + P_{core,\,RPF} + P_{harmonics,\,RPF} \tag{2.15}$$

Where:

$P_{copper,\,RPF}$ is the copper loss due to reverse power flow,

$P_{core,\,RPF}$, is the core loss influenced by voltage changes during RPF,

$P_{harmonics,\,RPF}$ is the loss due to harmonics generated by inverter-based DG systems.

Observed that reverse power flow, which occurs when distributed generation produces more power than is consumed locally, forces energy to flow from the distribution side back toward the substation. This reversal of power flow introduces several factors that can increase transformer losses:

1. Increased Load on Transformers: Transformers in distributed networks are traditionally designed for unidirectional flow, assuming a specific load profile. When power flows in reverse, transformers experience additional strain, increasing copper losses. The mismatch between transformer design and actual load conditions due to DG systems can exacerbate these losses.
2. Increased Voltage Variations: Reverse power flow often leads to voltage fluctuations along the network. As voltage levels deviate from the optimal range, transformers may operate outside their ideal efficiency zone, increasing both core and winding losses. High voltage can lead to increased iron losses, as core saturation may occur.
3. Bidirectional Power Flow and Overloading: Transformers are typically sized to handle local demand. However, with distributed generation, they are subjected to bidirectional power flow, which can cause periods of overloading. Overloading amplifies copper losses, especially during peak generation times when reverse power flow is most prominent.
4. Harmonic Distortion: Distributed renewable energy sources, particularly those connected via inverters (such as PV systems), introduce harmonic distortion into the network. These harmonics cause additional eddy current losses in the transformer core and increase I^2R losses in the windings, contributing to higher operational inefficiency and heat dissipation.

Using the ETAP software, the study models and analyzes the distribution network to quantify the effects of reverse power flow on transformer loading, which results in losses.

Using ETAP Load Flow Analysis has been done for a simple electrical network, the figures B.9 and B.10 in appendix B, clarify the impact of reverse power flow on the exist distribution transformer with different conditions. In figure B.9 the PV system is disconnected via the circuit breaker, while in figure B.10 the PV system is on grid and contributes 524kw with penetration about 50%, it is clear that the Transformer losses decrease.

Transformer losses continue decreasing, while the PV penetration doesn’t exceed 100 %.Then when the PV solar generates more power than the demand load in the grid, reverse power flows towards the distribution transformer.

In figure B.11 in appendix B, the PV generation meets 65% of the load demand. Transformer losses continue to decrease as more local generation is utilized, but no RPF occurs since generation remains below load demand, and figure B.12 in appendix B shows at 91% PV penetration, PV generation is still below the load demand, resulting in minimal transformer losses. On the other hand, the system is nearing a threshold where further increases in generation could trigger RPF. While the cases in figures B.13,B.14, B.15 and B.16 in appendix B depict the occurrence of RPF as PV generation exceeds load demand by 140%,183%,202%and 222%. The excess power flows back toward the transformer, leading to voltage rise and increased transformer losses and demonstrating the increase in I^2R losses in cable systems as reverse power flow increases, showing the importance of managing cable ratings and cooling in high-penetration scenarios.

Transformer Losses and the values of reverse power flow in each situation are tabulated in Table 2.3.

Table 2.3

Transformer Losses due to high PV generation

The load	PV generation-(PV generation /load demand)	The amount or reverse power flow	Transformer Losses
1 MVA –C.B is open	0-0	0	1.94kW+125555R
1mVA –C.B is closed	524 kW-55%	0	0.382kW +3.25kVAR
0.8MVA	524kW-65%	0	0.169kW+1.43KVAR
0.5MVA	524kW-91%	0	0.004kW+0.037kVAR
0.3MVA	524kW-140%	146.8kW	0.036kW+0.306kVAR
0.2MVA	524kW-202%	252.3kW	0.106kW+0.904kVAR
1MVA	3277kW-183%	1190kW	2.39kW+20.3kVAR
1MVA	4916kW-222%	196kW	6.29kW+53.3kVAR

Table 2.3 and figure B.17 in appendix B show the relationship between reverse power flow and transformer losses. As RPF increases with higher PV penetration, transformer losses also rise due to increased resistive and harmonic losses, particularly when the reverse power flow exceeds transformer capacity. The reverse power flow due to high penetration is affecting transformer aging. The increased copper, core, and harmonic losses associated with RPF lead to higher operational temperatures within the transformer. Excessive heat accelerates insulation degradation and can cause premature aging of transformer components, reducing overall equipment life. This thermal stress not only compromises reliability but can also necessitate more frequent maintenance or earlier replacement of the transformer, raising operational costs.

2.1.3 Impact on Protection Coordination of Distribution Systems

Protection coordination in electrical distribution networks ensures that protection devices such as circuit breakers, fuses, and relays operate in a hierarchical and coordinated manner to isolate faults, with minimal disruption to the rest of the network. These devices are traditionally designed based on the assumption of unidirectional power flow, from the substation towards the loads. However, the integration of distributed generation (DG) systems, especially with high penetration of renewables, introduces reverse power flow (RPF) into the network, complicating protection coordination.

An example of reverse power flow in normal and fault conditions can be described in figure B.18 [13] in Appendix B. As illustrated in figure B under typical circumstances protection relay R2 detects current flowing from the R1 side to the grid. 18. (a). Under normal circumstances there is no reverse current and no disruption. However as illustrated in figure B protection relay R2 detects the grids reverse flow when a bus fault arises. 18. (b). The current at the fault point is increased from its typical value during this fault occasion. There is a chance of damage at the fault point if R2 is not made to detect this reverse current flow direction and the fault current is not high enough to trip the R2 overcurrent protection. Protection devices are configured according to the downstream devices time-current characteristics fault current levels and power flow direction. Bypassing conventional protection settings power can return to the substation when RPF is caused by DG. Not being able to detect reverse currents may cause protection devices to malfunction leaving the fault isolated or resulting in delayed tripping. Long-lasting fault conditions equipment damage and cascading failures can result from this lack of reaction:

1. The presence of DG in the network can significantly alter fault current levels and the direction of fault currents:

a. Increased Fault Current Contribution: DG systems, especially inverter-based renewable sources, can contribute to the fault current. This increased current may exceed the capacity of protection devices, causing mal-operation or failure to isolate the fault. Traditional overcurrent relays may not be calibrated to handle such fault levels, leading to incorrect tripping.
b. Bidirectional Fault Currents: During RPF, fault currents may flow in the opposite direction. Protection devices not equipped with directional sensing may trip incorrectly or fail to detect the fault. For example, a relay installed to protect a feeder may not detect a fault when current flows from the DG source towards the substation.

2. Reclosers: Are widely used in distribution networks to automatically restore power after transient faults. They are typically designed for unidirectional power flow, where the source of fault current is only from the substation. In networks with RPF:

a. DG units may continue supplying fault current after a recloser opens, preventing the clearance of temporary faults.
b. When the recloser closes back in, if the fault persists and DG is still supplying power, it can lead to unsynchronized reclosing, causing additional equipment stress and possibly damaging the recloser or transformer.

3. Impact on Fuse Saving Schemes: In traditional systems, fuse-saving schemes are used where the upstream device (such as a breaker or recloser) briefly opens to allow the downstream fuse to clear a fault. With RPF:

a. Fuse fatigue: If RPF causes current to flow in the opposite direction, the fuse may blow prematurely or fail to operate altogether, disrupting the fuse-saving scheme.
b. Unintentional fuse operation: In some cases, DG may provide enough current to cause unintentional fuse blowing, leading to power outages that wouldn’t have occurred in a unidirectional flow scenario.

4. Coordination with Inverter-Based DG Systems: Most renewable energy sources, such as solar PV, are integrated into the grid through power electronic inverters. These inverters behave differently than traditional synchronous generators:

a. Limited fault current contribution: Inverter-based DGs have limited fault current contribution, which can affect the fault detection capabilities of traditional relays. Many protection systems rely on high fault currents to detect and isolate faults, but DG inverters may only supply a fraction of the fault current (typically around 1.1-1.5 times the rated current).
b. Harmonics and Distortion: Inverters may introduce harmonic distortion in the current, complicating the operation of protection devices, particularly those that rely on waveform analysis to detect faults.

Reverse power flow presents significant impacts to the existing protection coordination schemes in distribution networks, to ensure the reliability of the grid, it is essential to adapt protection systems to account for bidirectional power flow, increased fault current levels, and the unique behavior of inverter-based DG systems. Advanced technologies as directional relays and inverter controls are critical for mitigating the impacts of RPF on protection coordination.

2.2 Mitigation Strategies for Reverse Power Flow (RPF) in Distribution Network

The increasing in penetration levels of renewable energy systems, such as solar PV, to address the issues of reverse power flow impacts in electrical distribution network, some mitigation strategies can be implemented:

2.2.1 Battery Energy Storage Systems (BESS)

Definition of Energy Storage Systems (ESS)

Energy Storage Systems (ESS) are technologies which store energy for later use, allowing to use the excess energy when solar PV power generation exceeds the load demand and releasing it when needed. Energy Storage Systems (ESS) have many forms, such as batteries, pumped hydroelectric storage, and compressed air systems. The previous systems play an important role in balancing supply and load demand in the electrical power grid, enhancing the reliability of electrical networks**.** In the context of renewable energy resources, ESS is especially important, because it helps mitigate the intermittency of renewable sources as solar PV, ensuring that the excess energy generated during peak production times can be stored during periods of low generation. By providing backup power and managing peak demand, ESS contributes to the efficient operation of electrical grids.

Battery Energy Storage Systems (BESS)

Battery Energy Storage Systems (BESS) are the most widely used form of Energy Storage Systems, particularly in managing the issues produced by reverse power flow(RPF) in distribution networks with high penetration level of renewable energy. Battery Energy Storage Systems (BESS) offers flexibility in energy management by storing electrical energy, and releasing it when required.

Components of a Battery Energy Storage System (BESS)

A Battery Energy Storage System (BESS) consists of several components that work together. The major components of a BESS include:

1. Battery Cells; which are the core of the BESS, where energy is stored.
2. Battery Management System (BMS);which is responsible for monitoring the operation of the battery cells. It ensures optimal performance and safety by controlling parameters as temperature, voltage, and the State of Charge (SOC).
3. Power Conversion System (PCS); this component responsible for the conversion of electrical energy between AC and DC, this system is essential for ensuring proper energy flow.
4. Energy Management System (EMS); optimizes the overall performance of the BESS by deciding when to charge or discharge the battery, based on grid conditions, and energy demand

5. Thermal Management System; regulates the battery cells' temperature to ensure they operate efficiently and avoid overheating.
6. Protection and Control Systems; These systems provide protection by monitoring components and addressing any abnormalities, they include circuit breakers, and overcurrent protection devices to guard against short circuits and other faults.

Battery Energy Storage Systems (BESS) in Reverse Power Flow (RPF)

Battery Energy Storage Systems (BESS) are essential for addressing reverse power flow (RPF) issues in energy grids. They offer solutions to the impacts posed by integrating renewable energy sources.

1. Absorbing Excess Energy; BESS absorbs surplus energy generated by renewables as solar PV during low demand periods, this reduces the risk of excess power flowing back to the grid, which helps prevent transformer and distribution line overloads.
2. Stabilizing Voltage; Excess power from RPF can cause voltage spikes. BESS steps in by storing surplus energy, stabilizing voltage levels, and preventing fluctuations that could require expensive voltage control equipment.
3. Time-Shifting Energy; BESS enables the storage of surplus renewable energy when demand is low and releases it when demand peaks, such as during evening hours. This capability helps balance supply and demand while reducing the amount of reverse power sent back to the grid.
4. Reducing Renewable Curtailment;in some cases, renewable energy production is reduced to prevent RPF, BESS eliminates the need for curtailment by storing excess energy, which allows for maximum renewable energy use and supports grid operators.
5. Enhancing Grid Flexibilit; BESS provides greater flexibility for grid operators to manage the fluctuations of renewable generation. By storing energy during times of high level generation and releasing it when needed, BESS enhances grid reliability, and eliminates the occurrence of RPF.

Challenges of Using Battery Energy Storage Systems (BESS) to Mitigate Reverse Power Flow (RPF)

Many challenges were addressed for their widespread deployment and efficient operation. Below are the challenges associated with using BESS for managing RPF:

1. High Initial Costs: The installation of BESS involves significant upfront costs, primarily due to the high price of batteries, power conversion systems, and energy management systems. The cost per kilowatt-hour (kWh) of storage, though decreasing over time, remains a barrier for many residential, commercial, and utility-scale applications. The high capital costs can make it difficult for consumers, or utilities to justify the investment in BESS solely for mitigating reverse power flow (RPF), especially in regions where grid infrastructure is less stressed or where financial incentives are lacking.
2. Limited Battery Lifespan: Batteries, particularly lithium-ion, degrade over time and through repeated charge-discharge cycles, this degradation affects both the storage capacity and the efficiency of the BESS, reducing its ability to mitigate RPF effectively

over the long term. As the battery's performance declines, the system needs to be replaced, leading to additional costs. The shorter lifespan of batteries also affects the return on investment (ROI) for consumers and utilities, potentially reducing the economic attractiveness of BESS.

3. Environmental and Ethical Concerns: The production and disposal of batteries, particularly lithium-ion batteries, raise environmental concerns due to the extraction of raw materials like lithium, and nickel. Mining these materials has significant ecological impacts and raises ethical issues related to labor practices in some regions, these environmental and ethical challenges may lead to resistance against widespread adoption of BESS, especially if alternatives to battery chemistry are not developed or if recycling infrastructure for used batteries remains limited.
4. Energy Losses and Efficiency**:** While BESS can store excess energy generated from distributed energy resources, no system is 100% efficient. Energy losses occur during the conversion of energy from AC to DC (for storage) and from DC back to AC (for use), as well as due to battery self-discharge over time. These inefficiencies reduce the overall effectiveness of BESS in mitigating RPF. Energy losses can lead to reduced economic savings for users and utilities, making the investment in BESS less attractive unless efficiency is significantly improved.
5. Regulatory and Market Barriers: In many regions, regulatory frameworks and market structures are not yet optimized for integrating BESS into the grid. Barriers such as unclear rules for energy storage participation in energy markets, limited access to incentives, or restrictions on BESS providing ancillary services can hinder deployment. Without supportive policies, incentives, and clear market participation models, the adoption of BESS as a strategy for mitigating RPF will be slowed. Utilities and prosumers may find it difficult to justify the investment if market mechanisms do not adequately reward energy storage for its role in grid stabilization.
6. Grid Integration and Interoperability: Integrating BESS with existing grid infrastructure can be technically challenging, particularly in older grids that were not designed for bidirectional power flows or the dynamic needs of modern energy storage. Ensuring interoperability between different types of energy systems, distributed energy resources, and energy storage systems adds complexity to grid management.

7. Uncertain Revenue Streams**:** While BESS can provide multiple services (e.g., peak shaving), the revenue streams associated with these services may be uncertain or volatile. For example, participation in ancillary services markets may not guarantee consistent revenue, and the financial benefits of RPF mitigation alone may not justify the investment. The uncertainty of financial returns can discourage investment in BESS by both utilities and prosumers. Without stable and predictable revenue sources, the adoption of BESS as a key strategy for mitigating RPF may remain limited.
8. Capacity Limitations**:** While BESS can store and release energy to help mitigate RPF, the capacity of the system may be limited by the size of the battery. During periods of high renewable generation and low demand, the BESS could reach full capacity, after which excess power would still be exported to the grid, resulting in RPF. Insufficient storage capacity limits the ability of BESS to fully mitigate RPF, particularly in areas with large-scale distributed generation.

While BESS offers significant potential for mitigating reverse power flow(RPF), these challenges must be evaluated to ensure its effectiveness. Lowering costs, extending battery life, and improving regulatory frameworks are critical steps toward making BESS a scalable solution for managing reverse power flow in electrical distribution networks.

2.2.2 Shifting Load

Load shifting is the process of adjusting the timing of electrical consumption to periods when power generation is high and grid demand is lower. This is particularly important in systems with high penetration level of renewable energy sources (RES), such as solar PV, where the generation is intermittent and often does not coincide with peak demand periods. Load shifting plays a critical role in mitigating the effects of reverse power flow (RPF).

Load Shifting in Mitigating Reverse Power Flow

In electrical distribution grids with distributed generators (DG) from renewable sources as solar photovoltaic (PV), power generation may exceed local load demand, particularly during midday when solar generation peaks. This surplus power generated can cause RPF, where power flows back towards the substation, this causing voltage rise issues, increased transformer losses**,** and disruptions to protection coordination**.**

The figure B.19 [14] in appendix B represents a typical daily electricity consumption pattern without any load management or storage intervention and the figure B.20 [14] in appendix B represents daily electricity using load shifting.

Load shifting helps mitigate reverse power flow by encouraging consumers to shift their electricity consumption to periods of high renewable energy generation, thus reducing the excess power that would be exported back to the grid. By aligning electricity demand with the times when renewable generation is high, load shifting can minimize the occurrence of reverse power flow(RPF), improve grid stability by balancing supply and demand.

Load Shifting Strategies

Load shifting can be implemented through different strategies. These can be categorized into manual and automated methods:

1. Time-of-Use (TOU) Pricing: Time of Use (TOU) rates are a pricing structure used by utility companies, particularly in the context of electricity billing. Under TOU rates, the price of electricity varies depending on the time of day, typically divided into peak, off-peak, and sometimes shoulder periods.TOU tariffs incentivize consumers to shift their consumption to off-peak hours by offering lower electricity rates during times of high generation or low demand. For example, consumers may choose to run energy-intensive appliances like dishwashers, washing machines, or electric vehicles (EVs) during midday when solar generation is at its peak. See figure B.21 [9] in appendix B,assuming that the cost per kwh at 9 am-3am (the peak time) be less than other times, this TOU tariff incentivizes consumers to consume power during midday with lowest tariff. Reverse power flow alters the traditional consumption patterns where peak demand typically occurs in the afternoon or evening. With significant DG penetration, excess generation can lead to low or negative prices during sunny (midday).TOU tariffs need to be adjusted to reflect these changes, possibly incentivizing consumers to consume power during midday when reverse power flow is high and reduce consumption during evening peaks when grid demand is greater.

2. Demand Response Programs: Utilities can implement demand response programs where customers receive financial incentives to reduce or shift their electricity usage during periods of high renewable generation or when grid stability is at risk. These

programs can include direct load control, where utilities remotely manage some appliances like air conditioners or water heaters during peak renewable energy.

3. Smart Applications and Home Automation: Smart grids allows for intelligent load shifting without direct consumer intervention, smart appliances can be programmed to operate during times when renewable energy generation is high. This type of automated load shifting relies on advanced metering infrastructure (AMI).

Benefits of Load Shifting for Reverse Power Flow

Load shifting strategies in electrical distribution networks with high penetration of RES and RPF can offer many benefits:

1. Reduced Reverse Power Flow; load shifting can reduce the amount of energy flows back to the grid, minimizing the issue of voltage rise, and transformer losses.
2. Optimized use of renewable energy;load shifting ensures that a greater proportion of renewable energy is consumed locally, reducing the need for curtailment.
3. Decreased Grid Stress; load shifting can eliminate stress on grid infrastructure, particularly during peak periods of renewable generation. So this reduces the need for costly network upgrades.
4. Lower Energy Costs for Consumers: through TOU tariffs and demand response programs, consumers take advantage of lower electricity prices during periods of high renewable generation and reduce their overall energy bills.
5. Support for Grid De-carbonization: load shifting aligns electricity consumption with renewable energy availability, reducing reliance on fossil fuel-based power plants to meet peak demand, this contributes to the overall de-carbonization of the electricity grid.

Challenges of Load Shifting

Despite of load shifting advantages, there are also several challenges to its widespread implementation:

1. Consumer Awareness: Getting consumers to actively participate in load shifting programs can be challenging, especially if it requires changes in scheduling of appliance use, awareness campaigns and incentives are necessary to encourage adoption.

2. Technological Infrastructure: effective load shifting requires investment in smart meters, advanced metering infrastructure (AMI), and grid automation systems to allow real-time communication between utilities and consumers. Upgrading the grid to accommodate these technologies can be costly.
3. Impact on Non-Flexible Loads; not all loads are flexible. Some electricity consumption as heating, cooling, or essential services, may not be easily shifted to different time, limiting the overall potential for load shifting.

Load shifting is a critical strategy for managing the challenges of reverse power flow in distribution networks with high renewable energy penetration. It balances supply and demand, reduces grid congestion, and optimizes the use of renewable resources. However, effective implementation requires consumer participation and advanced grid management techniques to overcome the challenges associated with this strategy.

As renewable energy penetration grows, load shifting will become increasingly important for ensuring grid stability and minimizing the impacts associated with RPF. The transition to smart grids and the widespread adoption of energy storage systems will enhance the ability to shift loads effectively, enabling greater use of renewable energy and reducing reliance on traditional fossil fuel generation.

2.2.3 Smart Inverters and Zero Export Devices

Zero export devices and smart inverters can both be used in the context of managing renewable energy resources, they serve primary functions. Zero export devices are focused on ensuring that no excess power is exported to the grid, meeting specific regulatory requirements.

Smart inverter provides a broader range of functionalities aimed at supporting grid stability, including advanced grid support features and real-time communication capabilities. In some cases, a smart inverter can be configured to operate in a zero export mode, but it would offer additional features beyond export limiting.

Zero export devices

It simply means “No export power to the Grid”; the zero export controllers serve the goal of preventing any surplus power from being returned to the grid. Instead, it directs the generated solar energy towards powering the local load. Voltage and current are closely monitored and restricted based on the load needs. Through efficient energy flow management, the zero export controllers ensure that the inverter produces an amount of energy equal to or less than what the load requires.

As regulations on export control for residential and medium-sized commercial PV systems become more stringent, the zero export controllers emerge as the ideal solution!

Export limitation refers to the regulation of solar energy within the system by adjusting the set point of the inverters. The integrated power analyzer assesses the overall power at the coupling point and compares it to the controller’s adjustable set point. When the grid consumption exceeds the specified threshold, the input of solar energy is increased. Conversely, if the consumption drops below the set point, the input of solar energy is reduced.

The zero export controllers are offered in both single and three-phase configurations, accommodating up to ten diverse types of inverters and manufacturers. This all-in-one device seamlessly integrates a power analyzer, data logger, and controller. Zero export controllers have innovatively combined these three functionalities into a single component, ushering in a new era of comprehensive solutions. The zero export ensures that, at all times, the solar system is prevented from exporting power to the grid.

Sample Case for Zero Export Device (ZED)

Imagine a solar plant with a capacity of 10 kWp and a maximum load of 15 kWp. Let’s establish the minimum set point at 0.5 kWp and the maximum set point at 1 kWp. In a scenario where the required load is 7 kWp and the solar output is 8 kWp, the ZED will instruct the solar system to reduce power production to meet the 7 kWp demand. Conversely, if the load increases to 11 kWp while the solar system is generating 8 kWp, the ZED will allow the solar system to operate at its full capacity, with the additional power needed to be sourced from the grid, totaling 3 kWp.

If the grid input power falls within the specified minimum and maximum set points while reducing the solar system’s power output, the ZED will cease instructing the solar system to adjust its power output.

Features of Zero Export Devices

1. Smart Control;this key feature ensures the device smartly manages the power output of your solar system to prevent excess energy from being exported to the grid. It constantly monitors energy production & consumption, dynamically adjusting inverter output to match your real-time needs. This optimizes solar power usage and minimizes reliance on the grid.
2. Flawless Protection; this feature provides several safeguarding mechanisms to protect your system. It may include features like: Anti-islanding protection which automatically disconnects the solar system from the grid in case of power outages preventing unintended power flow back to the grid and Surge protection that shields your system from harmful voltage spikes that can damage equipment, in addition, ground fault protection which detects, interrupts ground faults and preventing potential electrical shock hazards.
3. Graphical Representation; this feature provides clear and easily understandable visuals of your energy data. It may includes; real-time power generation and consumption charts which monitor how much solar energy is being produced and used at any given moment. Furthermore, historical data summaries which track your energy usage trends over time and identify areas for improvement. Also system performance dashboards that gain insights into overall system health and efficiency.
4. Remote Monitoring; this feature allows you to access and manage your zero export devices remotely through a mobile application or web interface. This enables to view real-time and historical data; monitor your system performance from anywhere and anytime, also adjust settings by changing operating parameters as maximum grid import or export limits. In addition,receive alerts by getting notified about potential issues and system performance changes.

The challenges of using zero export inverters

Zero export devices presents some challenges, despite their benefits in mitigating reverse power flow (RPF). Here are several challenges associated with zero export devices

1. System Integration; ensuring compatibility with other system components and managing advanced features can be complex.
2. Financial Impact; limits on energy export may reduce financial returns and increase initial costs.

3. Maintenance; Increased system complexity can lead to higher maintenance needs and troubleshooting difficulties.
4. Energy Management; balancing energy generation, consumption, and storage while adhering to export limits can be challenging.
5. User Understanding; user mights struggle with the complexity of advanced features.

Smart Inverters

Smart inverter plays an essential role in eliminating the impacts of reverse power flow (RPF) in electrical distribution networks, especially with the increasing penetration of renewable energy systems (RES)as solar (PV).

Challenges of using smart Inverters

1. Voltage Regulation; the risk of over-voltage conditions in the network is one of the concerns with RPF. Smart inverters can adjust the reactive power output to help manage voltage levels. While traditional inverters, which only convert DC power to AC, smart inverters are capable of operating in a grid-supportive mode, they can provide both reactive power support and active power control, managing voltage rise caused by reverse power flow. By injecting or absorbing reactive power, they keep voltage within acceptable limits.
   a. Reactive Power Injection: if the voltage rises due to excess power generation and reverse power flow (RPF), the inverter injects reactive power to the grid, which reduces voltage levels.
   b. Reactive Power Absorption: in cases where the voltage is too low, the inverter absorbs reactive power, allowing the voltage rises to acceptable levels.

2. Power Factor Correction; reverse power flow (RPF) can distort the power factor in the network, leading to inefficiencies. Smart inverters can correct the power factor by adjusting the ratio of real to reactive power. This is especially useful in managing the power quality issues associated with excess renewable energy generation. By regulating the power factor, smart inverters reduce losses and improve the stability of the grid.
3. Frequency Stabilization; reverse power flow (RPF) also affects grid frequency if not managed properly, smart inverters are equipped with frequency response capabilities, allowing them to quickly adjust power output in response to frequency deviations; this

feature is essential for maintaining grid stability, particularly in areas with high renewable energy penetration.

4. Grid Communication and Control; smart inverters are integrated with advanced communication systems that allow them to interact with grid operators in real time. Through communication protocols such as IEEE 1547 and grid codes, these inverters can respond to grid signals and instructions to curtail power output or provide ancillary services as voltage and frequency regulation. This communication capability enhances the management of reverse power flow (RPF) by providing utilities with better control over distributed generation resources.
5. Ride-Through Capabilities; conventional inverter disconnect during disturbances, potentially exacerbating RPF issues, but smart inverters are designed to "ride through" voltage and frequency disturbances, maintaining their connection to the grid and continuing to provide support.
6. Active Power Curtailment; in situations where voltage or frequency regulation cannot mitigate the effects of RPF, smart inverters can also curtail the active power output of energy resources, this prevents further reverse power flow into the grid, effectively reducing the stress on grid infrastructure. The ability to curtail power ensures the grid remains within operational limits.

Smart inverters are essential for managing the challenges caused by reverse power flow in electrical distribution networks with high penetration levels of renewable energy systems. By offering advanced features such as voltage regulation, power factor correction and communication with grid operators, they help mitigate the negative impacts of RPF.

Chapter Three

Case Studies and Simulations

3.1 Case Study 1: Solar PV Integration in an Electrical Distribution Network

This case study illustrates the integration of solar photovoltaic (PV) systems into a typical distribution network and its impact on reverse power flow (RPF). Solar PV systems are one of the most widely deployed renewable energy technologies in residential, commercial, and industrial sectors. However, this case study clarifies the benefits of PV solar system as a Distributed Generator (DG) when the PV penetration does not exceed the limits.

Many scenarios have been applied by ETAP on the chosen electrical distribution network; to examine the impacts in various levels of PV Solar System penetration does not exceed the limits.

3.1.1 The electrical distribution network

As shown in the figure B.22 in appendix B, this electrical distribution network consists of 33 buses, power grid,14 step down transformers and different lump loads, transformers with rating 10 KV/0.38 KV,simulating reverse power flow scenarios due to high penetration of distributed generation (DG) in ETAP, the following scenarios can be set up to evaluate the effects on the grid and will help assess the impact of reverse power flow on voltage regulation, increasing transformer losses, and system stability.

3.1.2 Base Case Scenario -No Distributed Generation

This scenario represents the traditional operation of the distribution network without any DG connected. All generation is supplied from centralized power plants or substations. Power flows from the substation to the load without any reverse power flow. Assume that the power factor for all loads is 100%.

The amount of total power generated from the grid power,which is equal to 56.557 MW +1.020MVAR.As mentioned before this analysis for the electrical network without PV solar system. The total amount of the generation power is 56.667MW, in table 3.1 some of voltage % buses and TR-losses are recorded.

Table 3.1

Voltage % and transformer losses for some buses and transformers without solar PV

Bus number	Voltage % Without PV Solar	Transformer ID	TR-losses Without PV Solar
2	97.264	T1	2.2kW+13.1Kvar
3	97.171	T2	2kW+12.2kVAR
4	97.417	T3	2kW+12.3kVAR
8	95.266	T4	1.9kW+11.6kVAR
11	95.647	T5	2.6kW+15.5kVAR
15	95.575	T6	2.5kW+14.9kVAR
18	95.530	T7	2.3kW+13.9kVAR
22	94.880	T8	2.2kW+13.2kVAR
25	95.218	T9	2.1kW+12.9kVAR
28	94.733	T10	2.2kW+13.1kVAR
30	91.960	T11	41.9kW+251.6kVAR
33	94.427	T12	2.2kW+13.1kVAR

3.1.3 Case Scenario - adding Distributed Generation solar PV with penetration 20%

See Figure B.23 in appendix B and table 5,this analysis has been done after adding a solar PV system to the following buses, figure B.23 in appendix B displays the network status after integrating a solar PV system with 20% penetration. Key measurements, such as voltage levels at various buses, indicate the initial impacts of PV penetration on the distribution system before significant reverse power flow issues arise.

In this case the network operates efficiently, with minimal voltage rise and no reverse flow power (RPF), as the PV generation is within local demand, in this case represented by figure B.23 in appendix B, the total power generated from PV is 12126.3kW.

$$So, PV\ penetration\ level\ = \frac{12126.3}{56557} \cong 20\%. \qquad (3.1)$$

Figures B.24 and B.25 in appendix B, illustrates the benefits of adding PV solar system at bus 30 and bus 33.The voltage level rises, for example at bus 33 Voltage % = 94.25%,and after adding solar PV was equal to 96.97%, transformer losses connected to these buses decreases for example,at bus 33 the transformer #14 losses was equal to

8.12kW+48.7kVAR, but after adding solar PV to the bus T14 losses decreased to 0.746kW+4.48kVAR.

Table 3.2 displays voltage % with adding solar PV to various buses and also displays some transformer losses in the electrical network.

Table 3.2

Voltage %, transformer losses with PV penetration 20%

Bus number	Voltage % With PV penetration 20%	Transformer ID	TR-losses With PV penetration 20%
2	98.115	T1	2.1kW+12.8kVAR
3	98.341	T2	2kW+12kVAR
4	97.417	T3	2kW+12kVAR
8	96.897	T4	1.9kW+11.3kVAR
11	97.358	T5	2.6kW+15.5kVAR
15	97.187	T6	2.4kW+14.5kVAR
18	97.260	T7	2.3kW+13.6kVAR
22	96.513	T8	0.1kW+0.4kVAR
25	96.935	T9	2.1kW+12.8kVAR
28	96.914	T10	0.1kW+0.4kVAR

After adding PV to many buses with PV penetration 20% the voltage % increases to all buses in the network, and most transformers' losses decrease. And power delivered from the power grid decreases to 45.723 MW.

3.1.4 Case Scenario -adding Distributed Generation Solar PV with PV penetration 40%

This case analysis has been done after adding Solar PV systems more than previous case at the various buses to achieve more power generated from solar PV, where the amount of power generated from solar PV was 23980.1kW.

$$So\ PV\ penetration\ level\ = \frac{23980.1}{56557} \cong 40\%. \qquad (3.2)$$

Table 3.3 illustrates the scenario where solar PV penetration reaches 40%. Voltage levels at specific buses may approach upper limits, but RPF remains minimal, and transformer losses are still reduced.

Table 3.3

Voltage %, transformer losses after adding solar with PV penetration 40%

Bus number	Voltage % With PV penetration 40%	Transformer ID	TR-losses With PV penetration 40%
2	98.115	T1	2.1kW+12.8kVAR
3	98.341	T2	2kW+11.6kVAR
4	99.038	T3	2kW+11.6kVAR
8	97.426	T4	0kW+.2kVAR
11	97.800	T5	2.5kW+15.1kVAR
15	97.545	T6	2.4kW+14.4kVAR
18	97.619	T7	0.1kW+0.6kVAR
22	97.045	T8	0.1kW+0.4kVAR
25	97.378	T9	2.1kW+12.8kVAR
28	97.273	T10	0.1kW+0.4kVAR
30	97.034	T11	2.2kW+13.4kVAR
33	97.332	T12	0.1kW+0.4kVAR

By comparing table 3.2 and table 3.3, it is clear that there is no presence for reverse power flow, and after adding PV to many buses with acceptable penetration lower than power consumed by the loads, the voltage % increases, and transformer and cable losses decrease.

3.1.5 Case Scenario -adding Distributed Generation solar PV- With PV penetration 60%

This case study presents a case study where PV penetration is increased to 60%, showing the impact on voltage and losses in transformers and cables. The data indicates significant reverse power flow and highlights the need for mitigation strategies, by adding more solar PV to the electrical network the amount of power generated from PV reaches to 36106.2kW.

$$So, PV\ penetration\ level\ = \frac{36106.2}{56557} \cong 60\% \tag{3.3}$$

Table 3.4

Voltage %, transformer losses with PV penetration 60%

Bus number	Voltage % With PV penetration 60%	Transformer ID	TR-losses With PV penetration 60%
2	98.115	T1	2.1kW+12.4kVAR
3	98.341	T2	1.9kW+11.6kVAR
4	99.038	T3	1.9kW+11.6kVAR
8	97.742	T4	0kW+0.2kVAR
11	99.705	T5	0.2kW+1kVAR
15	99.468	T6	0.1kW+0.8kVAR
18	99.707	T7	0.1kW+0.6kVAR
22	99.367	T8	0.1kW+0.5kVAR
25	99.609	T9	0.1kW+0.5kVAR
28	99.521	T10	0.1kW+0.4kVAR
30	98.951	T11	2.3kW+13.8kVAR
33	99.426	T12	0.1kW+0.5kVAR

In case of 60% PV penetration, also there is no presence for reverse power flow, and after adding PV to many buses with acceptable penetration lower than power consumed by the loads the voltage % increases, and transformer and cable losses decrease.

3.2 Case Scenario - Distributed Generation solar PV- with high PV penetration

In this case the PV generation is fixed but the load consumption is reduced. So that the amount of power being generated by the PV solar system exceeds the demand load. Bus 24 is analyzed with photovoltaic (PV) penetration of 107%. The generated power exceeds the demand load, resulting in a reverse power flow of 28.5 kW. The voltage level (V%) reaches 101.4%, while transformer losses are minimal at 0.005 kW and 0.003 kVAR, reflecting a system operating at acceptable efficiency under high PV penetration. Bus 24 with a PV penetration of 150%. The reverse power flow significantly increases to 153.9 kW due to the surplus PV generation. The voltage level (V%) rises to 101.6%, and transformer losses are calculated at 0.147 kW and 0.884 kVAR, indicating increased stress on the distribution transformer under higher PV penetration, according to Figure B.26 and Figure B.27 in appendix B, the load flow analysis for Bus 24, the reverse power flows towards the distribution transformer, causing rising voltages levels and transformer losses.

3.2.1 Case - Distributed Generation solar PV with high PV penetration= 109%

In this case reduced load consumption, to achieve high PV Penetration. See table 3.5 and figure B.28 in appendix B,in this case the demand load has decreased with PV generation at peak time,so high PV penetration (about 109%) occurred.

The total demand power decreased from 56.557MW to 36.308MW.

$$\text{So; Pv penetration}=\frac{PV\ generation}{total\ power\ of\ the\ grid}=\frac{39.753MW}{36.308MW}=109\% \qquad (3.4)$$

High PV penetration produced reverse power flow in most feeders as shown in figure B.28 in appendix B About 3413kW reverse power flows backward to the power grid. The voltage % and transformers losses recorded in table 3.5 related to the case study PV penetration =109%.

Table 3.5

Voltage %, transformer losses with PV penetration 109%

Bus number	Voltage % With 109% PV penetration	Transformer ID	TR-losses With 109% PV penetration
2	99.616	T1	0.4kW+2.4kVAR
3	99.891	T2	0.4kW+2.4kVAR
4	99.848	T3	1.9kW+11.5kVAR
8	100.561	T4	0+0.1kVAR
11	100.426	T5	0.3kW+1.6kVAR
15	100.263	T6	1.9kW+11.4kVAR
18	100.583	T7	0.3kW+1.6kVAR
22	100.487	T8	0kW+0.1kVAR
25	100.054	T9	0.1kW+0.5kVAR
28	100.275	T10	0.3KW+1.6kVAR
30	99.674	T11	2.9kW+17.6kVAR
33	100.566	T12	0.1kW+0.5kVAR

The results for this case (PV penetration=109%):

1. Presence for reverse power flow towards the power grid with an amount of 4313 kW, which means more penalties.
2. Assume the price of RPF kW=0.39 Shekel.

Then the penalty will be =0.39x3413=1331.07 Shekel

1. After reducing demand load the buses voltages % increases to unacceptable levels for the buses with reduced load.
2. The transformers losses decreased in some transformers and increased in other transformers according to the reduction amount of the load connected to this transformer.
3. If you compare with Table 3.4 and Table 3.5, the Voltage% and T -losses increases with the case of PV penetration 109%, that's belong to the load variation; the load that had been reduced was near the power grid. So the amount of reverse power flow raised to 3413kW.

3.2.2 Case - Distributed Generation solar PV with High PV penetration= 190%

In this case reduced the load consumption, to achieve high PV penetration more than previous case. See table 3.6 and figure B.29 in appendix B, in this case the demand load has decreased with PV generation at peak time, so high PV penetration (about 109%) occurred. The same power was generated from a PV distributed generator, and the total demand power decreased from 56.557MW to 22.486MW.

Reverse power =19798kW=19.798MW.

$$\text{So; Pv penetration}=\frac{PV\ generation}{total\ power\ of\ the\ grid}=\frac{42.284MW}{22.486MW}\cong 190\% \qquad (3.5)$$

High PV penetration produced reverse power flow in most feeders as shown in the figure B.29 in appendix B, which is about 19.79MW reverse power flows backward to the power grid.

Table 3.6

Voltage %, Transformer losses with PV penetration 190%

Bus number	Voltage % with 190% PV penetration	Transformer ID	TR-losses with 190% PV penetration
2	101.235	T1	0.1kW+0.8kVAR
3	101.153	T2	0.4kW+2.4kVAR
4	101.845	T3	1.1kW+7.7kVAR
8	101.833	T4	0.3kW+1.5kVAR
11	101.631	T5	0.8kW+4.7kVAR
15	101.988	T6	0kW+0kVAR
18	101.662	T7	0.3kW+1.5kVAR
22	101.669	T8	0.3kW+1.5kVAR
25	101.671	T9	0.1kW+0.9kVAR
28	101.907	T10	0.3KW+1.6kVAR
30	102.591	T11	4kW+24kVAR
33	101.645	T12	0.1kW+0.5kVAR

The results for this case (PV penetration=190%):

Presence for reverse power flow towards the power grid with an amount of 19798 kW, which means more penalties.

Assume the price of RPF kW=0.39 Shekel.

Then the penalty will be =0.39x19798=7721.22 Shekel

After reducing demand load the buses voltages % increases to unacceptable levels.

The transformers losses decreased in some transformers and increased in other transformers according to the reduction amount of the load connected to this transformer and reverse power flows towards the transformer.

3.2.3 Extra case for bus 30 with different high PV penetration levels

In figure B.30 in appendix B, bus 30 reveals a reverse power flow (RPF) of 63 kW. The load demand at Bus 30 is1760 kW, with a voltage level (V%) of 101.5%. The total system losses are measured at 0.025kW and 0.149 kVAR, focusing on the reverse power flow contribution to the overall energy dynamics.

In figure B.31 in appendix B, bus 30 reveals a reverse power flow (RPF) of 312 kW. The load demand at Bus 30 is 1511 kW, with a voltage level (V%) of 101.9%. The total system losses are measured at 0.6 kW and 3.6 kVAR, focusing on the reverse power flow contribution to the overall energy dynamics. Bus 30 under conditions of a reverse power flow (RPF) of 813 kW in figure B.32 in appendix B, the load demand is reduced to 1010 kW, with the voltage level (V%) increasing to 102.6%. System losses are calculated at 4.03 kW and 24.2 kVAR, indicating a significant increase in reverse power flow compared to the previous scenario. And in figure B.33 in appendix B, bus 30 with a reverse power flow (RPF) reaching 1065 kW, the load demand is further reduced to 758.9 kW, with the voltage level (V%) at 102.9%. System losses in this scenario are recorded at 6.87 kW and 41.2 kVAR, marking the highest level of reverse power flow among all cases analyzed; the increasing in RPF causes rising in voltages at bus30 and increases T-losses. See table 3.7 and table A.1 in appendix A.

Table 3.7

Voltage rise% VS. RPF

Reverse power flow(Kw)	Voltage % At bus 30
63	101.5
312	101.9
813	102.6
1065	102.9

3.2.4 Solar PV RPF problem in Jericho city

The initial phase involved establishing a 100 kW peak solar power plant as part of the sewage treatment project on a 1-dunum area in 2014, with panels rated at 235 W peaks.

A partnership was formed with the electricity company to build a 1.5 MW peak station on the same plot of land, covering 20 -dunum, from 2018 to 2020, with panels rated at 250 W peaks.

Later, the partnership with the electricity company was renewed, and another solar power plant was set up on the same 10-dunum plot of land between 2022 and 2024, using panels rated at 685 W peaks with double-face generation technology.

Due to the increasing load on the sewage treatment plant and its expansion to serve the city's sewage network, the demand increased with the rising flow of treated water. By the end of the year, it is expected that approximately 70% of homes in the city will be connected. To achieve the goal of making the sewage treatment plant a green facility, the municipality of Jericho needs to establish an 800 kW peak plant at the sewage treatment site. This will cover all plant loads, both day and night, with a maximum instantaneous operational capacity of 248 kWh.

Since the sewage treatment plant operates day and night, calculations show that an 800 kW peak capacity is needed, considering the existing 100 kW peak solar plant, to fully cover the sewage plant’s day and night consumption. During the day, consumption will be met, and the surplus will be fed back into the electrical grid to be reclaimed at night when the sun is down.

With all the solar plants connected to the same point, the planning department at the Jerusalem Electricity Company found that there is a significant reverse power flow issue. The nature of Jericho’s power demand reaches 100% in summer but drops to 10% in winter and spring. This poses a problem in winter, as the demand falls by 90%, leading to reverse power on the network lines and transformers. This will cause increased power losses on the grid. The 800 kW peak station in Jericho, under existing conditions, will generate 600-650 kW, and the sewage station’s existing load is 248 kW. The grid’s absorption capacity, according to the company’s planning department, is 100-150 kW peaks; while the reverse flow will nearly double. The connection will be directly to the high-voltage point at 33 kV, using a 1000 kVA step-up transformer.

Proposed Solutions

1. Using BESS to store the excess power and use it later, but there are a lot of challenges of this solution such as high costs, battery degradation over time, efficiency losses in charging and discharging, technical challenges in integration, environmental impacts, regulatory and market limitations, and maintenance needs. These factors can limit their performance and economic viability.
2. Reduce the station’s capacity to match the network’s capacity. This solution is not suitable for the sewage treatment plant.

3. Connect the Solar PV plant to a control system that activates or disconnects strings and inverters based on the network’s capacity. However, this would result in losses for the owner.(using zero export devices and smart inverters).
4. Segment the Solar plant by changing its location according to the network’s capacity at the Jerusalem Electricity Company and create a transit agreement for small stations. In this case, the owner would need to provide land at specified locations on the grid to establish small stations.
5. Increase transmission lines from the area to the electricity company’s network to enhance the network’s capacity. This would involve connecting areas in the network to the plant and distributing the capacity via transmission lines, potentially connecting to cities like Ramallah or Bethlehem. However, this solution would be costly for the company.

3.3 Economic Feasibility Analysis for Battery Energy Storage Systems (BESS), Smart Inverters, and Load Shifting

The economic feasibility of battery energy storage systems (BESS), smart inverters, and load shifting as strategies to mitigate reverse power flow issues must be analyzed in terms of upfront costs, operational savings, return on investment (ROI), and long-term financial sustainability.

3.3.1 Battery Energy Storage Systems (BESS)

Upfront Costs

1. Cost of Batteries: the cost of BESS is typically measured in $/kWh. Current market rates for lithium-ion batteries, the most common type, range from $250 to $500 per kWh depending on the capacity and region.

   Assume, a 1 MW / 2 MWh battery system might cost $500,000 to $1,000,000.
2. Installation Costs: installation costs include labor, land acquisition (if necessary), and integration with the grid. This can add an additional 20-30% to the total project cost.
3. Inverter and Control Systems: BESS requires specialized inverters to convert stored DC energy into AC for grid integration. costs for inverters are around $100-$150 per kW.

   For a 1 MW system, this might add $100,000 to $150,000.

Operational Costs

1. Maintenance Costs: annual maintenance costs for BESS systems typically range from 1% to 2% of the system's upfront cost, depending on the type of technology and the environment.

   For a $1 million system, this would be $10,000 to $20,000 per year.
2. Battery Degradation: over time, the performance of batteries will degrade, requiring replacements every 10-15 years. This adds a long-term replacement cost.

Revenue and Savings

1. Energy Arbitrage: BESS can store excess energy during periods of low demand (and lower prices) and release it during peak periods when prices are higher, generating revenue.

   If energy prices differ by $0.05 per kWh between low and peak periods, and the battery stores and discharges 1,000 kWh per day, this could generate $50 per day or $18,250 per year.
2. Peak Shaving: BESS can reduce demand charges by providing power during periods of peak demand. If demand charges are $10 per kW and the system offsets 500 kW of peak demand, the annual savings could be $60,000.

Assuming the peak is reduced by 500 kW (i.e., the system offsets the entire peak demand), and the demand charge remains at $10 per kW, the savings calculation is as follows:

Annual Savings=500kW×$10per kW×12 billing periods=$60,000.

Reduction in Reverse Power Flow Losses: By storing excess energy, BESS reduces reverse power flow losses, though this benefit is harder to quantify directly.

Return on Investment (ROI)

Based on revenue streams and savings, a typical ROI for BESS systems ranges from 6-10 years. However, the ROI can vary significantly depending on local energy tariffs, battery performance, and grid conditions.

3.3.2 Smart Inverters

Upfront Costs

1. Inverter Cost: Smart inverters cost slightly more than conventional inverters due to their advanced features, such as reactive power control and voltage regulation. Costs are around \$100-\$150 per kW.
   For a 1 MW system, this translates to \$100,000 to \$150,000.
2. Installation Costs: Installation typically adds another 10-20% of the cost, or around \$10,000 to \$30,000 for a 1 MW system.

Operational Costs

1. Maintenance: Smart inverters are relatively low-maintenance, with annual maintenance costs around 1% of the initial investment, or about \$1,000 to \$1,500 per year for a 1 MW system.
2. Software Updates: Periodic updates to the control software may be required to ensure optimal performance, though these are generally included in maintenance contracts.

Revenue and Savings

1. Reduction in Reverse Power Flow Issues: Smart inverters help manage voltage fluctuations and provide grid support, reducing the risk of reverse power flow penalties or grid instability. This indirect benefit improves system efficiency but may not have a direct monetary value unless penalties for power quality are imposed.
2. Increased Solar Generation: By preventing curtailment, smart inverters can allow more solar energy to be exported to the grid, maximizing revenue. If curtailment is reduced by 5% in a 1 MW solar farm generating 1,500 MWh annually, an additional 75 MWh could be exported, potentially earning \$3,750 annually at \$0.05 per kWh.

Return on Investment (ROI)

The ROI for smart inverters is generally short, around **3-5 years**, as their upfront costs are relatively low and the efficiency gains are immediate.

3.3.3 Load Shifting (Demand-Side Management)

Upfront Costs

1. Infrastructure and Smart Metering: Implementing load shifting requires investment in smart meters and load control systems to monitor and manage energy usage. Smart meters cost around \$100-\$200 each, and load management systems can cost \$50,000 to \$100,000, depending on the scale.
2. Customer Incentives: Incentivizing consumers to shift their loads (e.g., via Time-of-Use (TOU) tariffs) may require initial subsidies or rebates to encourage participation.

Operational Costs

Administrative Costs: Ongoing costs include managing the TOU tariff program, customer outreach, and maintaining the load management infrastructure. These costs vary but can range from \$10,000 to \$30,000 per year, depending on the size of the program.

Revenue and Savings

1. Reduced Grid Strain: Shifting loads during high generation periods reduces reverse power flow and the associated operational challenges, such as power losses or equipment degradation.
2. Cost Savings for Consumers: Consumers benefit from lower electricity prices during off-peak hours, and utility companies avoid having to upgrade infrastructure to accommodate reverse power flow. In areas with significant load shifting, utilities can reduce capital expenditures by 5-10%.
3. Energy Arbitrage: Utility companies can optimize energy procurement by purchasing cheaper electricity during off-peak periods and using it during peak demand.

Return on Investment (ROI)

Load shifting programs have a long ROI period, around 5-10 years, this depending on the participation rate of the program. The savings from reduced grid stress and deferred capital upgrades can be significant over time but may take years to realize fully. See table A.2 in appendix A.

3.3.4 Conclusion

1. BESS is the most expensive solution but provides high potential for energy arbitrage and grid support.
2. Smart Inverters are cost-effective and offer immediate benefits in managing reverse power flow and grid stability with a relatively short ROI.
3. Load Shifting requires consumer engagement and has a longer ROI but can provide significant savings by reducing grid stress and avoiding infrastructure upgrades.
4. Choosing between these solutions depends on the grid conditions, regulatory framework, and available financial resources.

Chapter Four

Conclusion

This thesis explored the effects of reverse power flow in electrical power systems. Our investigation into the conditions under which reverse power flow occurs, the impacts on system stability, and the mitigation strategies have yielded several important findings.

Firstly, we identified that reverse power flow primarily results from high levels of distributed generation (DG), particularly from renewable sources such as solar PV panels. This phenomenon leads to many challenges for traditional power grids designed for unidirectional flow from central generation to end-users. Our analysis confirmed that reverse power flow can cause voltage regulation issues, losses in transformers and system protection complications.

Secondly, this thesis examined various strategies to mitigate the effects of reverse power flow. These include advanced grid management systems, such as BESS, smart inverters, zero export devices, and demand side management. Our findings suggest that the appropriate solution depends on the specific grid conditions and available financial resources.

In conclusion, while reverse power flow presents several challenges, it also offers opportunities for innovation in power system design and operation. Continued research and development in this area are crucial to ensure that power systems can adapt to the evolving energy landscape. Future research should focus on optimizing control strategies for distributed generation, developing advanced forecasting models, and exploring the economic impacts of reverse power flow on utility operations.

By addressing these issues, we can move towards a more reliable and sustainable power system that accommodates the growing contribution of renewable energy sources while maintaining stability and performance.

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Appendices

Appendix A

Tables

Table A.1

Reverse power flow VS. Transformer losses

Reverse power flow (Kw)	Transformer losses for T11
63	0.025Kw+0.149kVAR
312	0.603Kw+3.62kVAR
813	4.03Kw+24.2kVAR
1065	6.87Kw+41.2kVAR

Table A.2

Economic Feasibility for Mitigation Strategy

Mitigation Strategy	Upfront Costs	Operational Costs	Revenue & Savings	ROI
BESS	$500,000 to $1,000,000 (for 1 MW/2 MWh)	$10,000 - $20,000 annually	Energy arbitrage, peak shaving, reduced losses	6-10 years
Smart Inverters	$100,000 to $150,000 (for 1 MW system)	$1,000 - $1,500 annually	Enhanced solar export, reduced curtailment	3-5 years
Load Shifting	$50,000 to $100,000 (infrastructure)	$10,000 - $30,000 annually	Reduced grid strain, deferred capital upgrades	5-10 years

Appendix B

Figures

Figure B.1

Simple electrical network connected to solar PV with a 1 MVA load, showing the impact on voltage rise

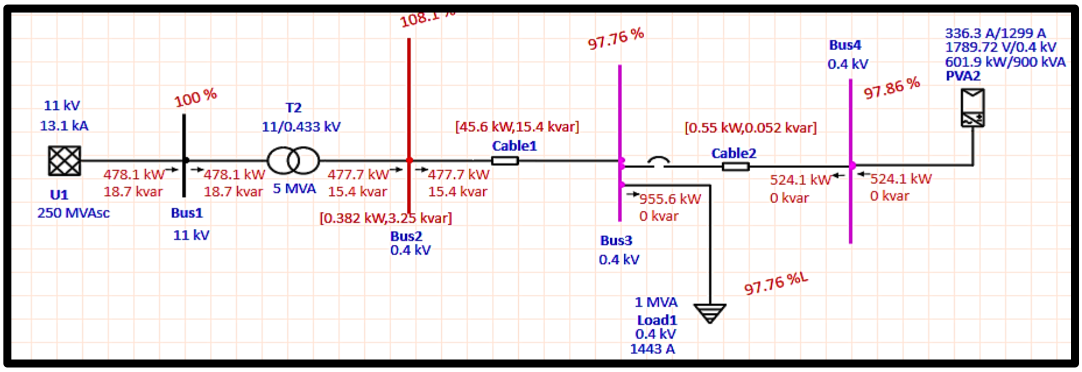


Figure B.2

Simple electrical network with connected solar PV -0.8MVA load

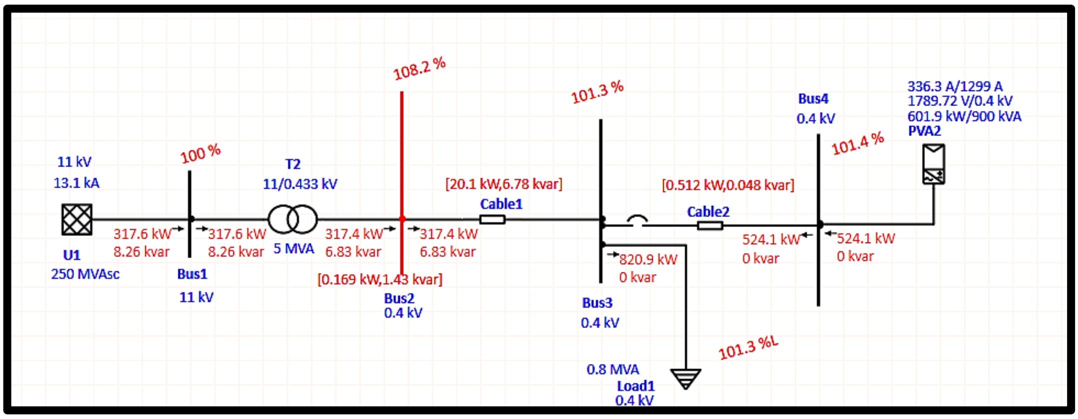


Figure B.3

Simple electrical network with connected solar PV -0.4MVA load

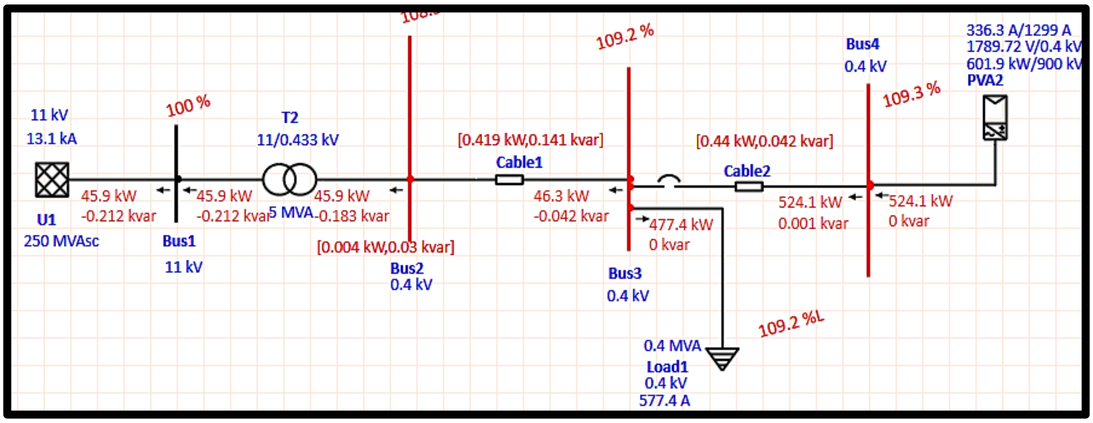


Figure B.4

Simple electrical network with connected solar PV -0.3MVA load

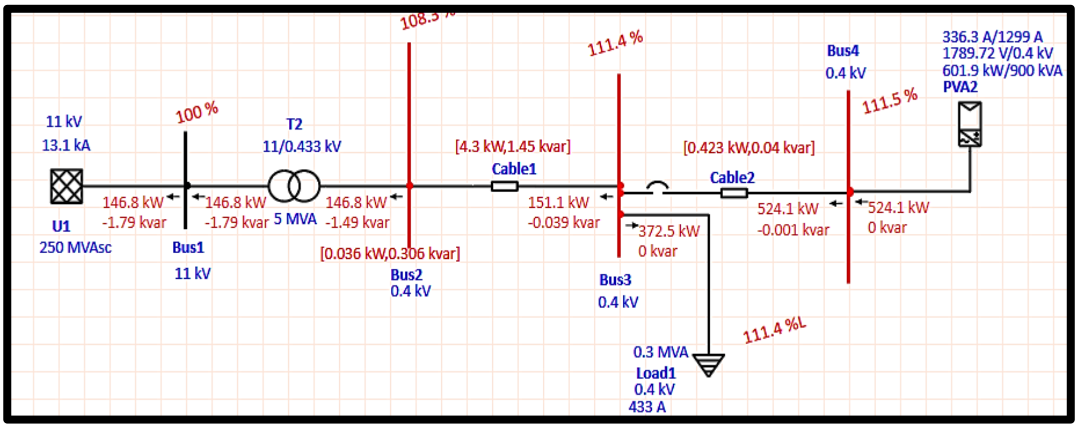


Figure B.5

Simple electrical network with connected solar PV -0.2MVA load

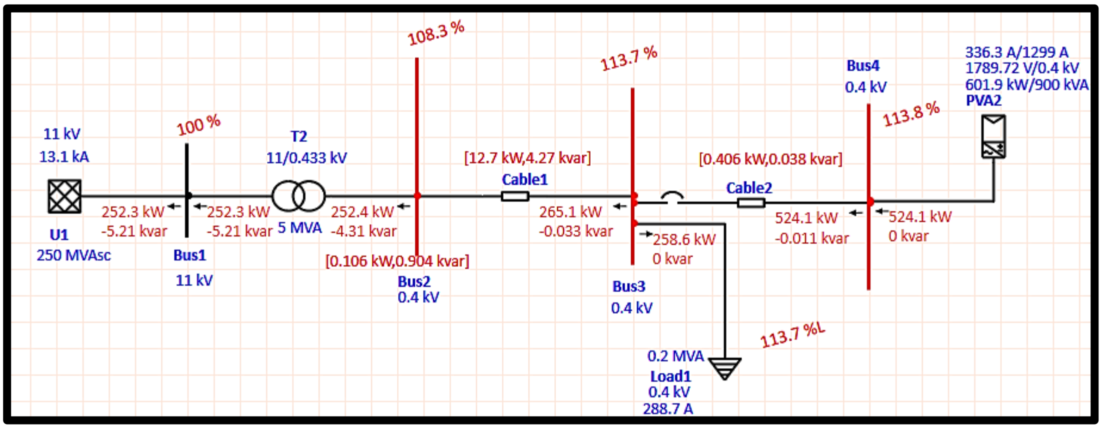


Figure B.6

Voltage rising issue VS. High PV penetration

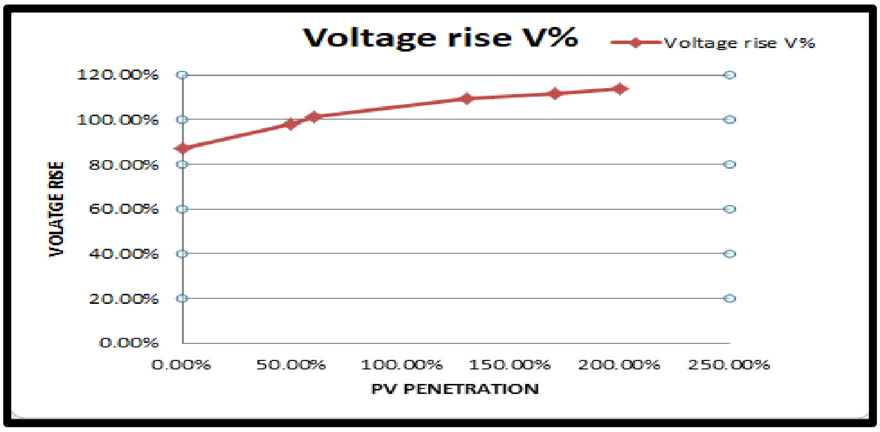


Figure B.7

Simple electrical network with 2 solar PV -1MVA load

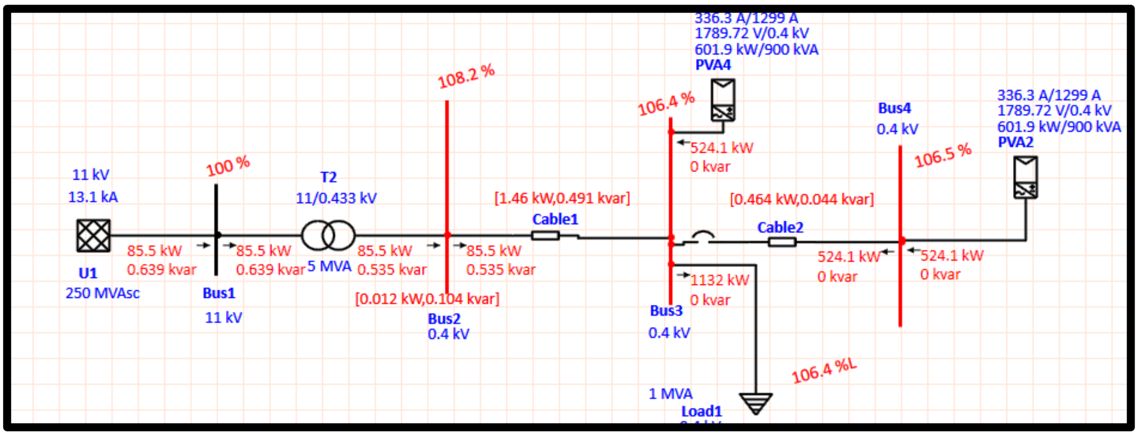


Figure B.8

Simple electrical network with 2 solar PV -Reverse Power Flow

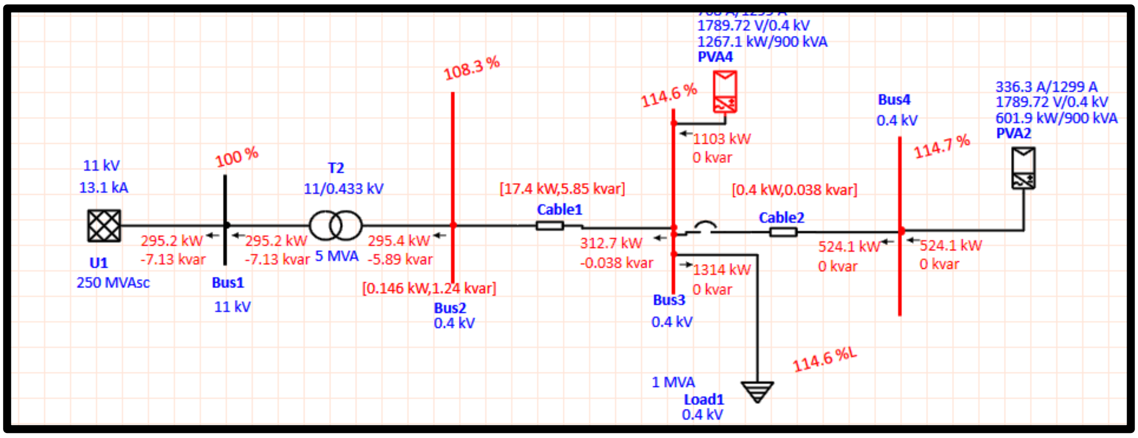


Figure B.9

Electrical network with CB.open –no RPF

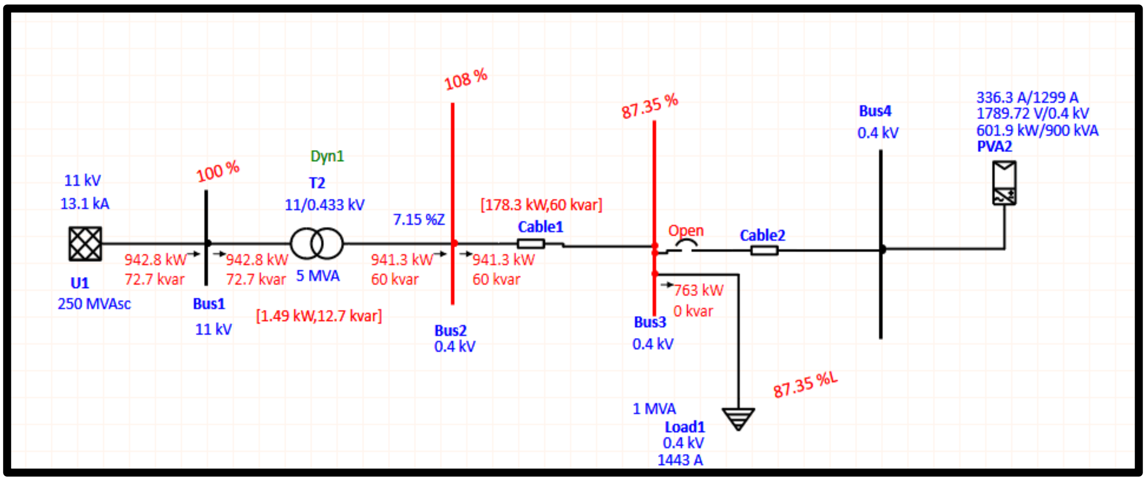


Figure B.10

PV generation /load demand) percentage= 55%

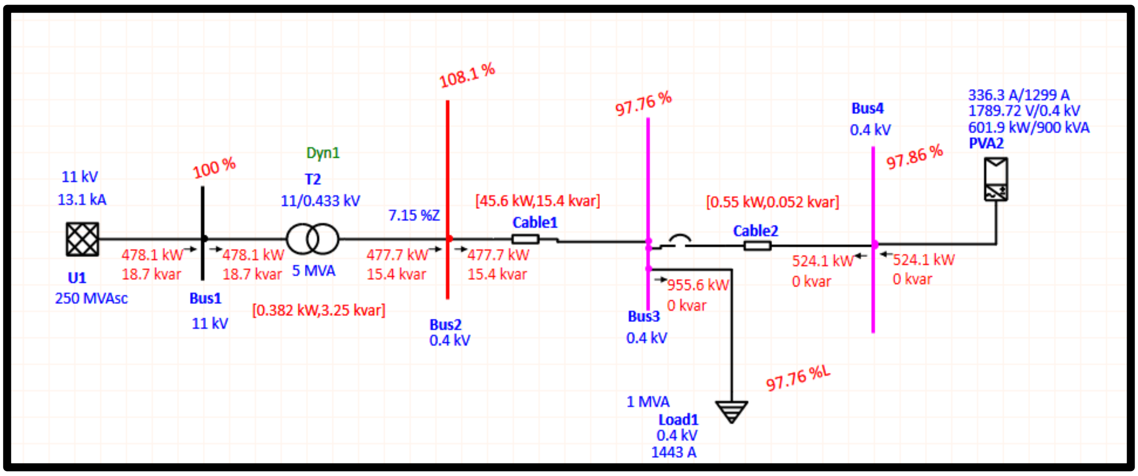


Figure B.11

PV generation /load demand) percentage=65%

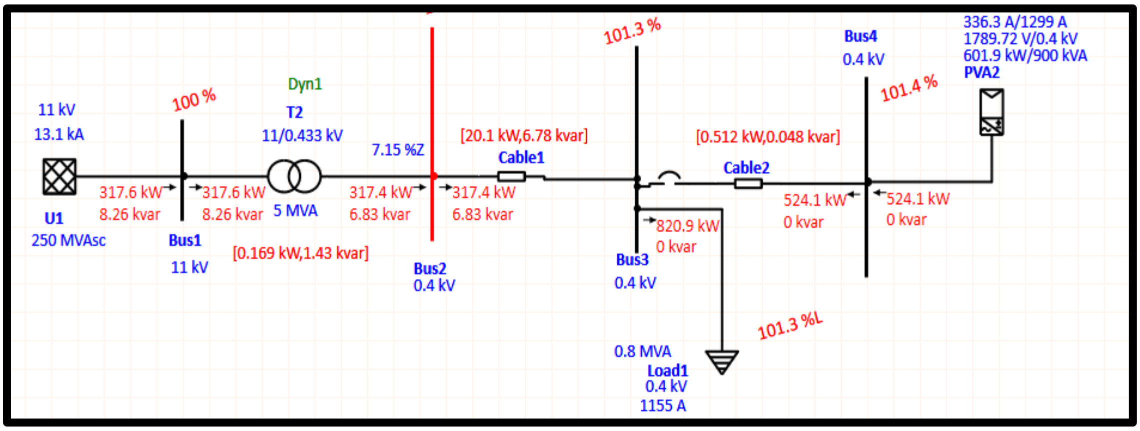


Figure B.12

PV generation /load demand) percentage= 91%

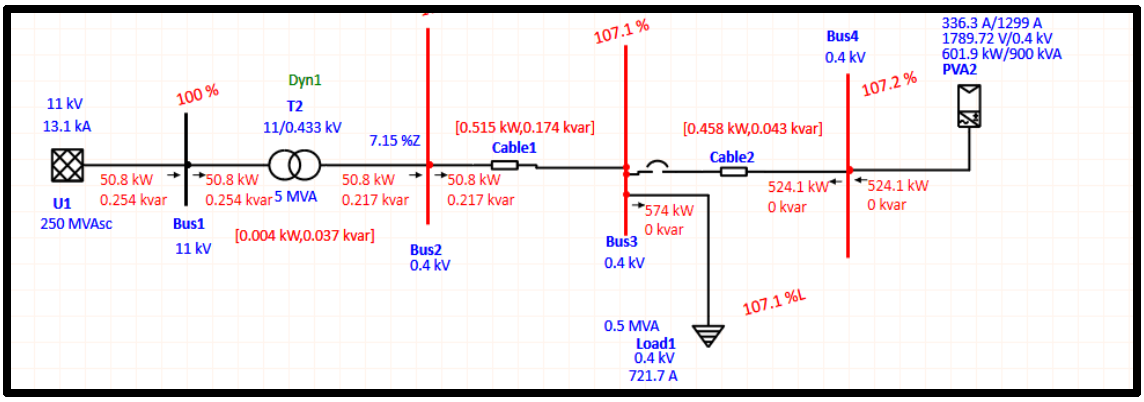


Figure B.13

PV generation /load demand) percentage=140%

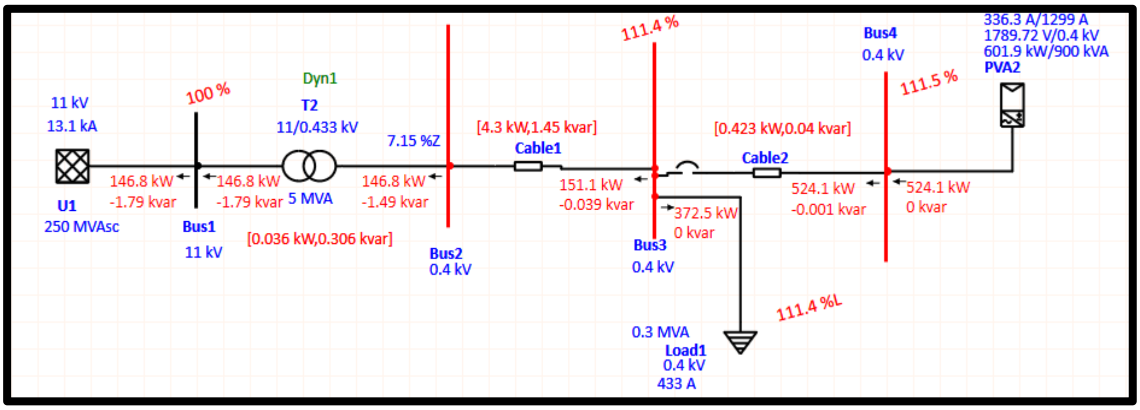


Figure B.14

PV generation /load demand) percentage=183%

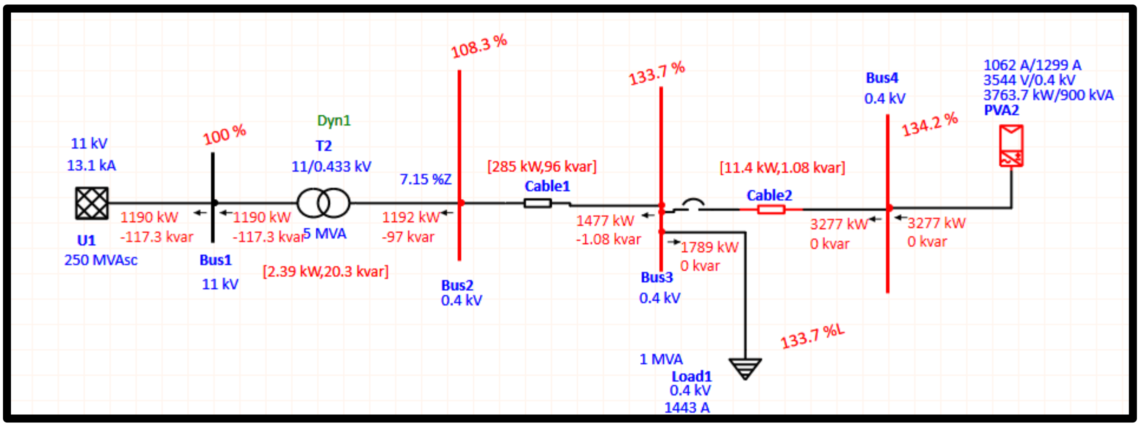


Figure B.15

PV generation /load demand) percentage=202%

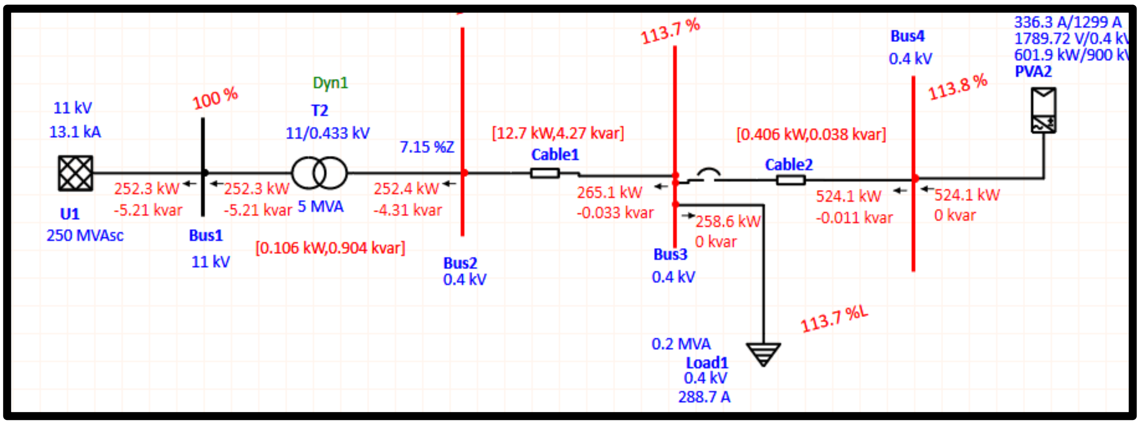


Figure B.16

PV generation /load demand) percentage=222%

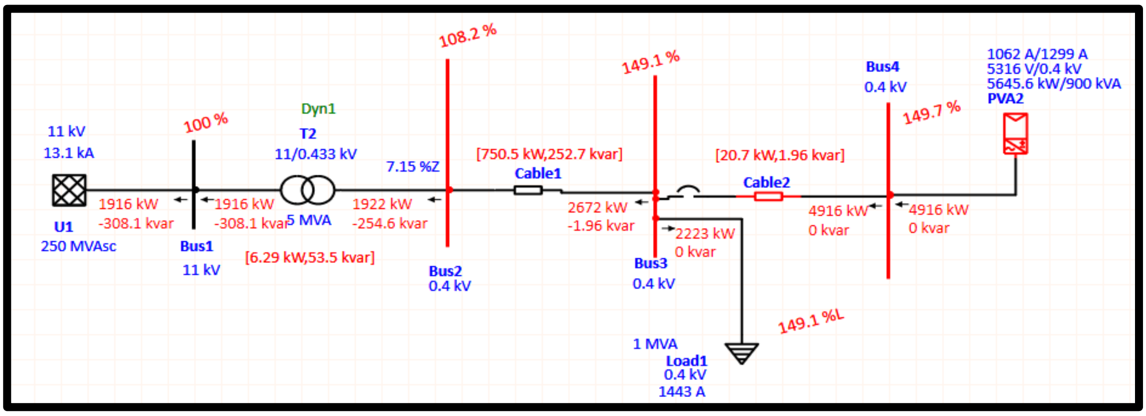


Figure B.17

RPF Vs. Transformer Losses

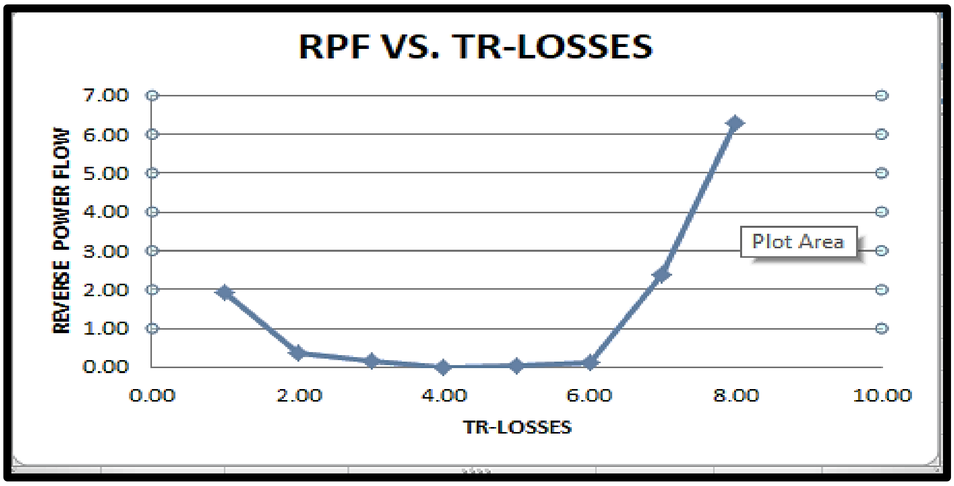


Figure B.18

Reverse power flow in normal and fault conditions

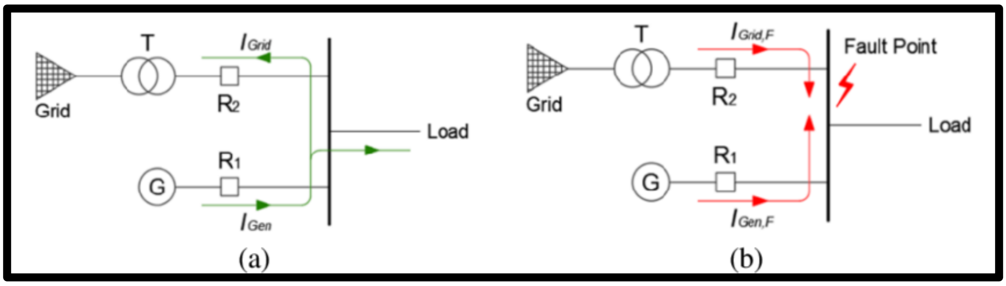


Figure B.19

Normal Daily Electricity Use

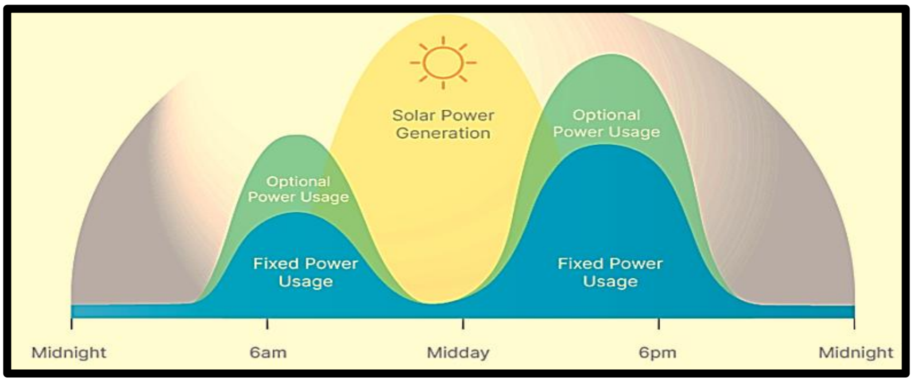


Figure B.20

Daily Electricity Use LOAD SHIFTING

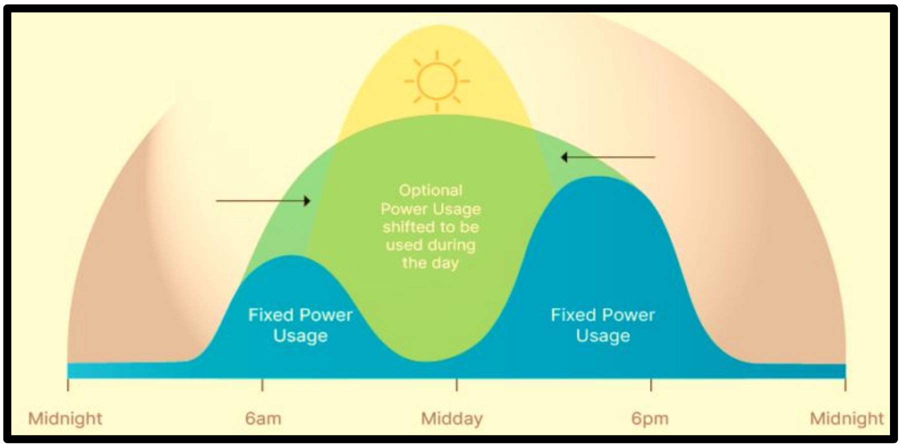


Figure B.21

TOU Concept

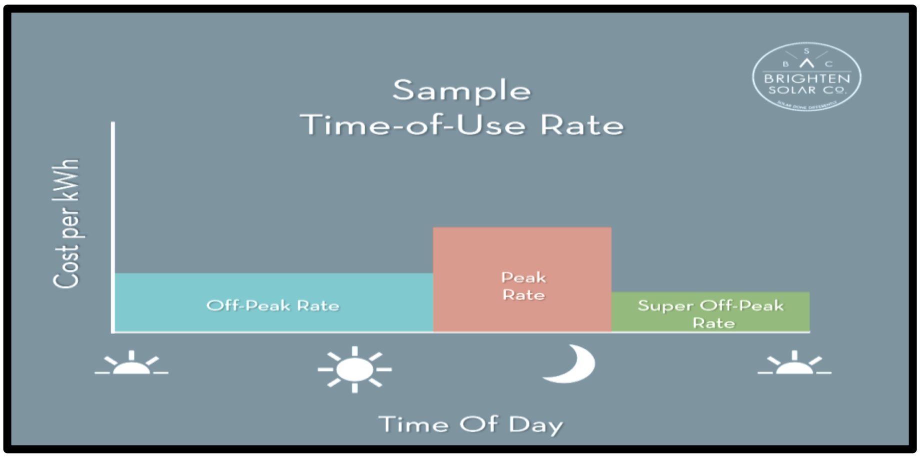


Figure B.22

The electrical distribution network without solar PV -analyzed by ETAP

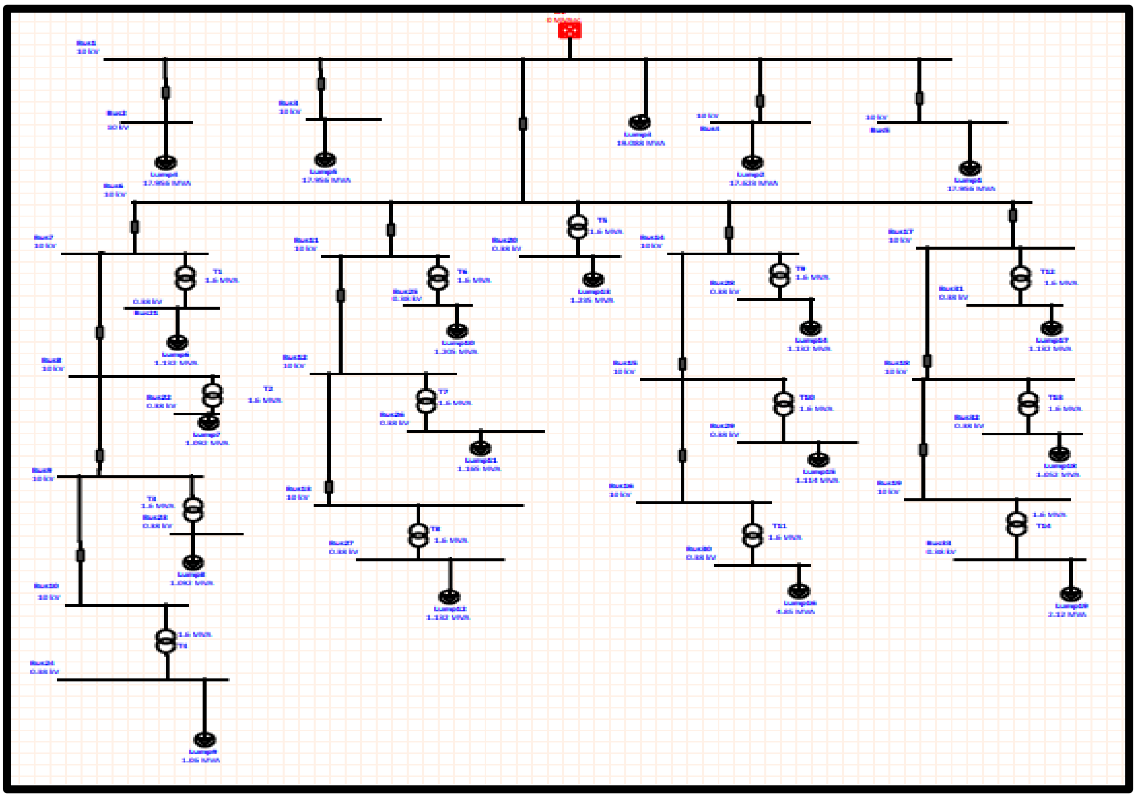


Figure B.23

The electrical distribution network with PV penetration 20%

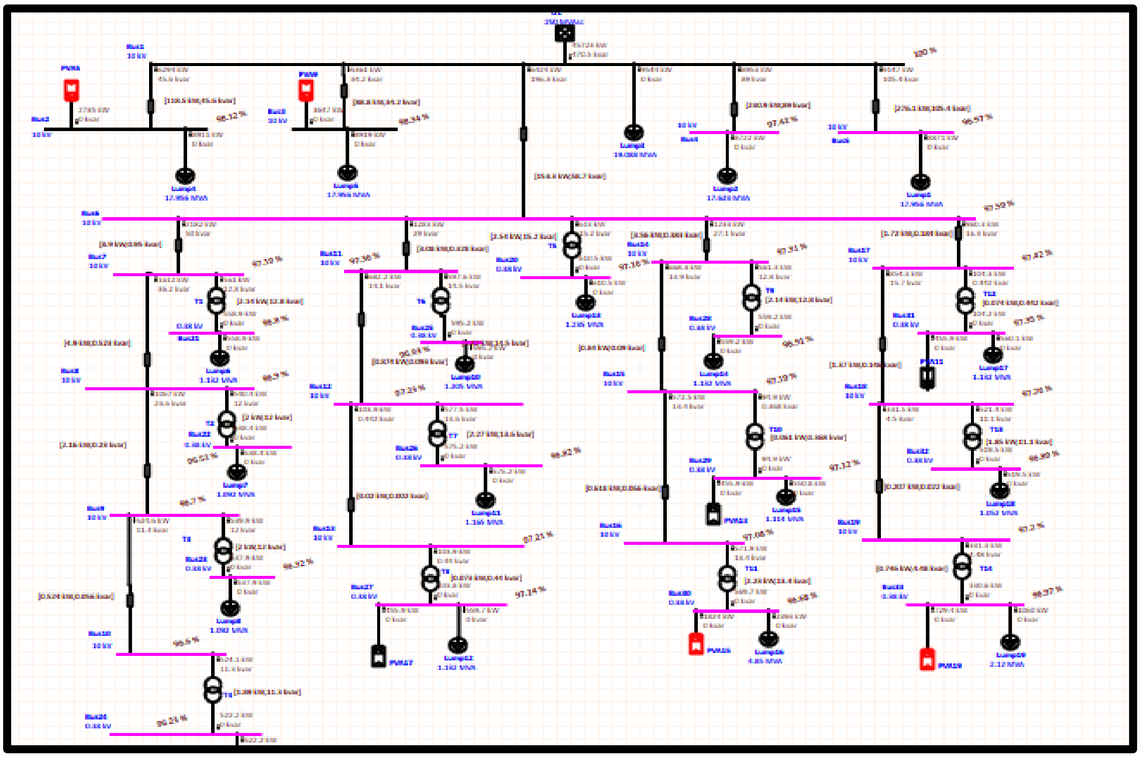


Figure B.24

Bus 30 & Bus 33 -without PV

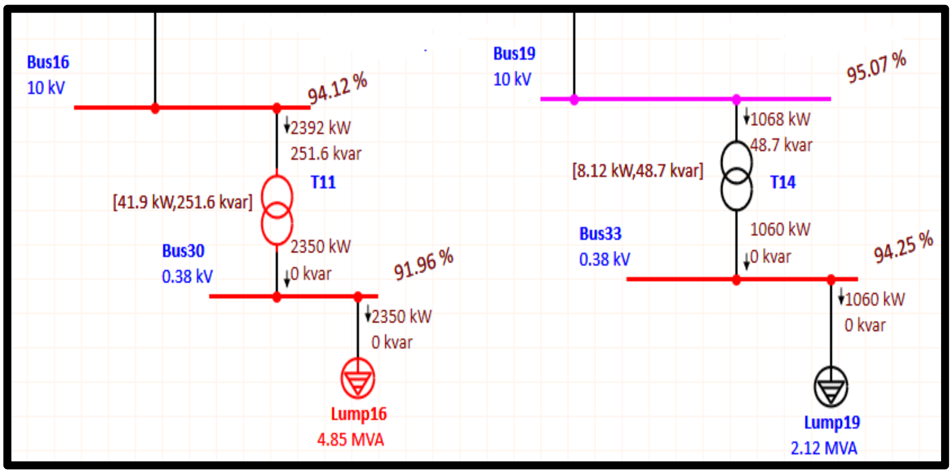


Figure B.25

Bus 30 &Bus 33 -with adding PV

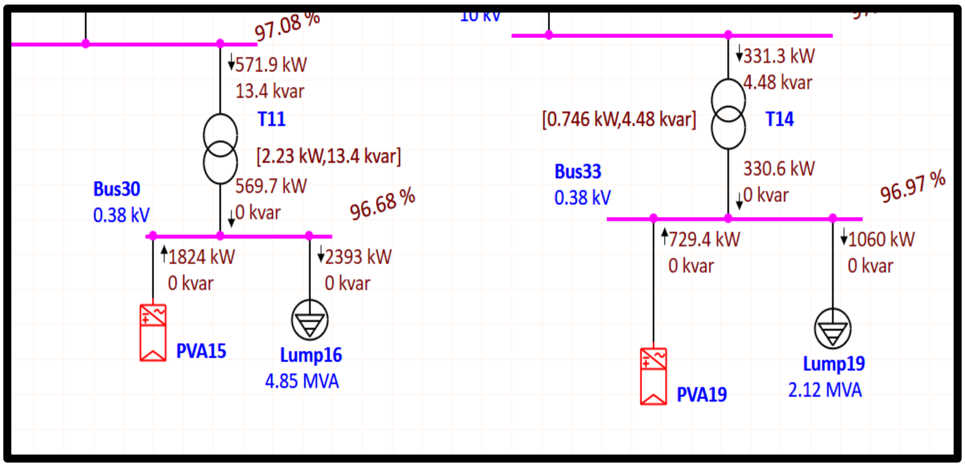


Figure B.26

Bus 24-PV penetration 107%

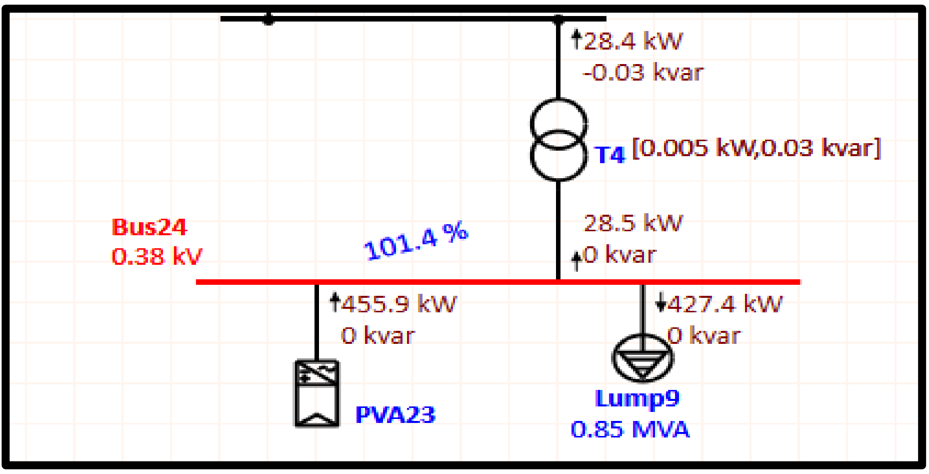


Figure B.27

Bus 24-PV penetration 150%

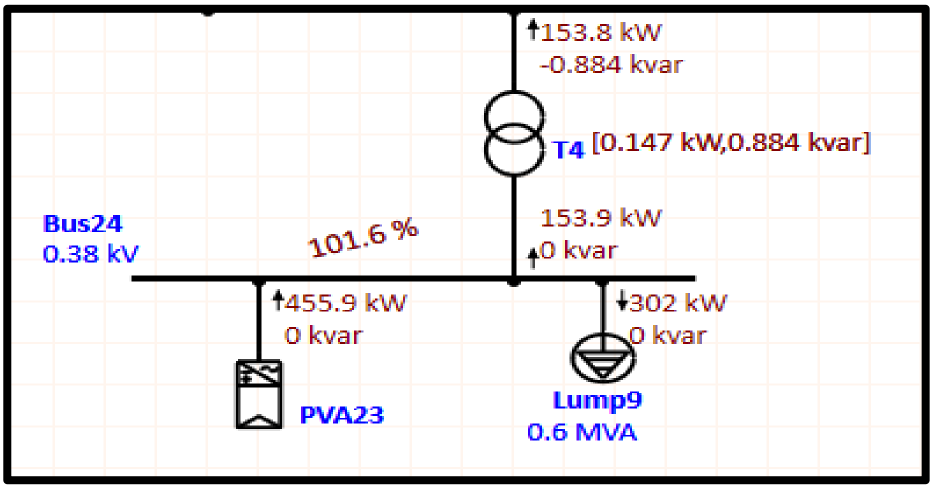


Figure B.28

Distributed Generation solar PV with high PV penetration=109%

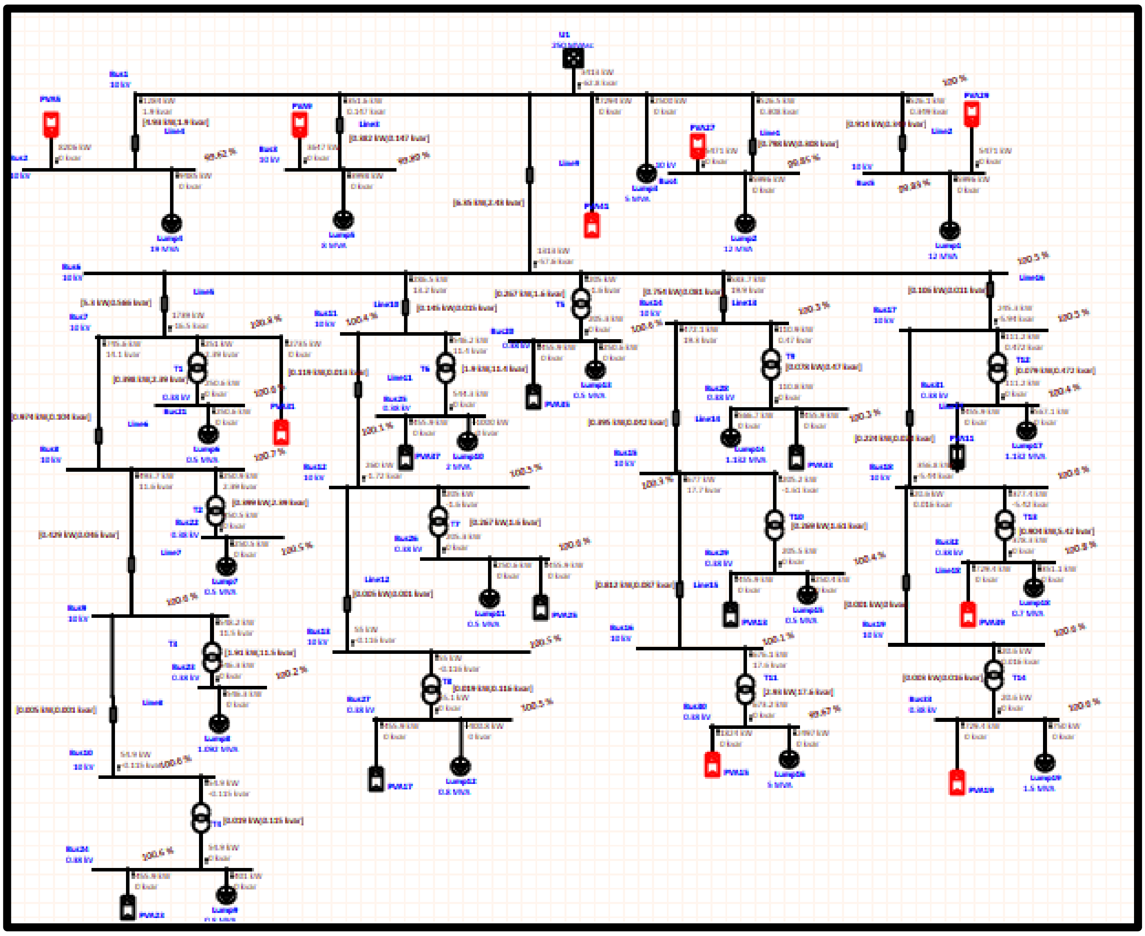


Figure B.29

Distributed Generation solar PV with high PV penetration=190%

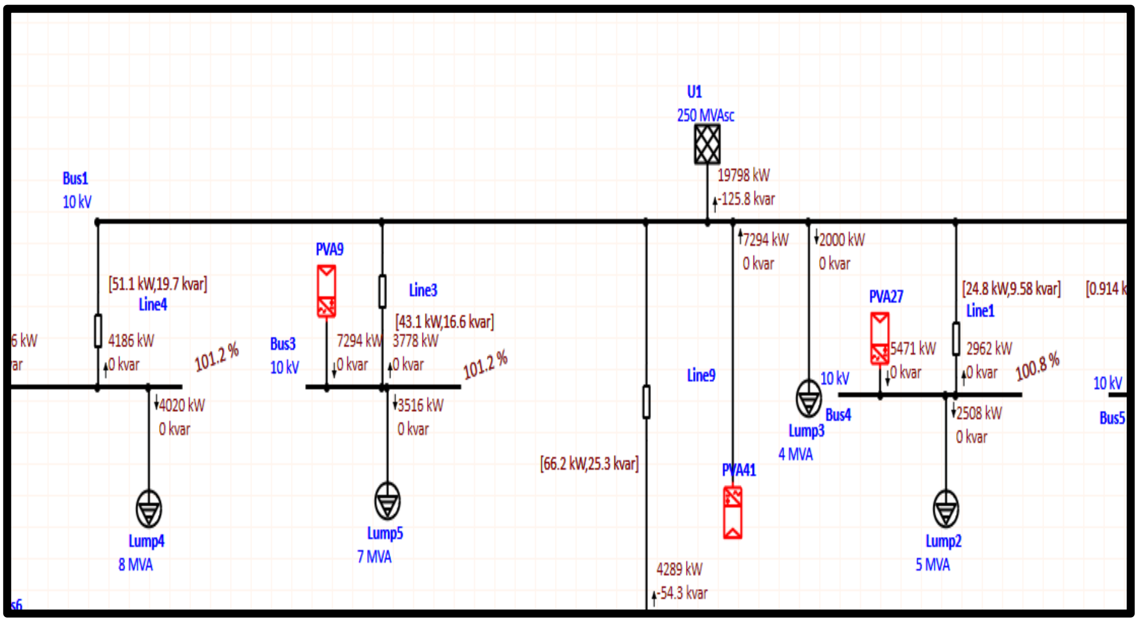


Figure B.30

Bus 30 analysis showing reverse power flow (RPF) of 63kW

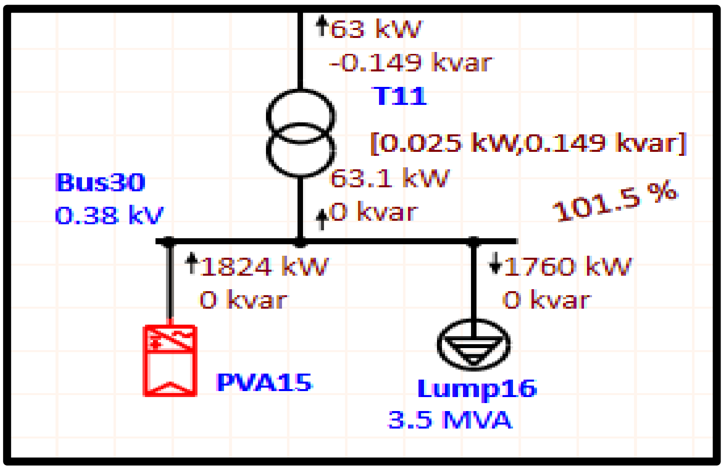


Figure B.31

Bus 30 analysis showing reverse power flow (RPF) of 312kW

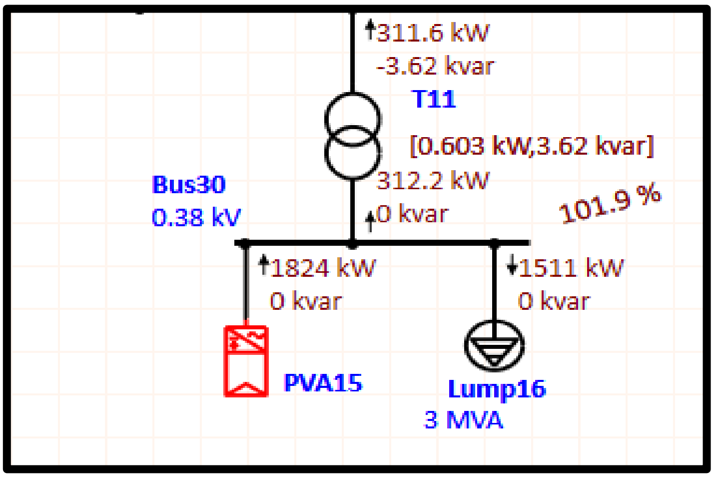


Figure B.32

Bus 30 with RPF 813kW

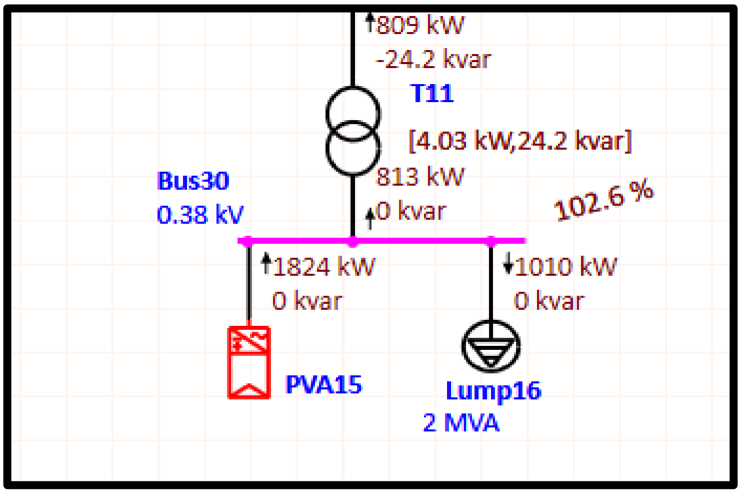
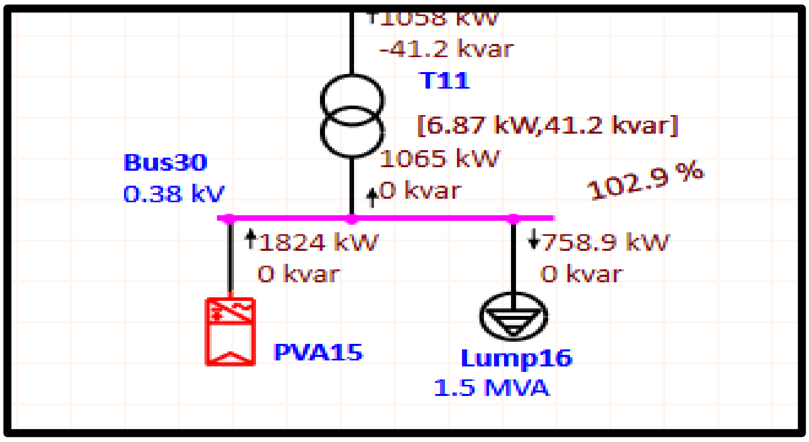


Figure B.33

Bus 30 with RPF 1065kW



جامعة النجاح الوطنية
كلية الدراسات العليا

تأثيرات وطرق معالجة ظاهرة الانسياب المعاكس للقدرة الفعالة في الشبكات الكهربائية التي تتضمن مستوى عالي من مصادر الطاقة المتجددة

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قدمت هذه الرسالة استكمالا لمتطلبات الحصول على درجة الماجستير في هندسة القوى الكهربائية، من كلية الدراسات العليا، في جامعة النجاح الوطنية، نابلس – فلسطين.

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الملخص

لقد أدى الانتشار المتزايد لأنظمة الطاقة المتجددة (RES)، وخاصة التوليد الموزع (DG) مثل الطاقة الشمسية الكهروضوئية (PV)، إلى تحويل شبكات توزيع الطاقة الحديثة. وفي حين تقدم هذه التكنولوجيا فوائد بيئية واقتصادية، إلا أنها تقدم أيضًا تحديات تقنية كبيرة. ومن أكثر القضايا أهمية تدفق الطاقة العكسي (RPF)، والذي يحدث عندما يتجاوز توليد الطاقة من المصادر الموزعة الطلب المحلي، مما يتسبب في تدفق الطاقة مرة أخرى نحو شبكة توزيع الكهرباء.

تتناول هذه الأطروحة تأثيرات تدفق الطاقة العكسي بسبب الاختراق العالي في شبكة توزيع الكهرباء؛ يتم إجراء تحليل مفصل لتقييم كيفية تأثير RPF على الجهد وخسائر المحولات. من خلال ETAP، تم محاكاة شبكة توزيع كهربائي مع 33 ناقلاً و14 محولًا 10 كيلو فولت / 0.38 كيلو فولت و19 حملاً متصلاً بالناقلات. تم إجراء محاكاة الشبكة عن طريق إضافة نظام طاقة شمسية كهروضوئية وملاحظة الفوائد.تم زيادة عدد مجموعات الطاقة الشمسية الكهروضوئية المتصلة بالشبكة للوصول إلى مستويات اختراق الطاقة الشمسية المختلفة 20٪، 40٪، 60٪، وفي هذه المستويات من مساهمة النظام الكهروضوئي في انتاج الطاقة لا يوجد تدفق طاقة عكسي باتجاه الشبكة الكهربائية، ترتفع الجهود إلى مستويات مقبولة وهذا يؤثر على تحسين الشبكة الكهربائية ويقلل من خسائر المحولات، ولكن إذا كان تدفق الطاقة المنتجة من خلال نظام الطاقة الشمسية يتجاوز حمل المستهلك ، تتدفق الطاقة العكسية نحو محولات التوزيع مما يتسبب في خسائر وارتفاع في الجهد.

تم محاكاة الشبكة عن طريق تقليل الطلب على الحمل للوصول إلى مستويات من الطاقة الناتجة من خلال انظمة الطاقة الشمسية بنسبة 109٪ و190٪، وكانت كميات تدفق الطاقة العكسية تتزايد مع نقصان الطاقة الكهربائية المطلوبة للمستهلكين وانتاج طاقة كهربائية من انظمة الطاقة الشمسية في وقت الذروة. وتسببت هذه الظاهرة بحدوث العديد من المشاكل على الشبكة اهمها التدفق العكسي للقدرة الكهربائية الفائضة باتجاه الشبكة ,وأدى ذلك الى ارتفاع الجهد ومشكلة خسائر المحولات. تم اقتراح استراتيجيات لتخفيف هذه المشكلة مثل نظام تخزين طاقة البطارية، وادارة احمال المستهلكين من خلال أطر تنظيمية تطرحها البلديات و شركات الكهرباء في المنطقة.وأجهزة التصدير الصفرية والعاكسات الذكية. وتم إجراء التقييم لكل استراتيجية تخفيف ويعتمد الاختيار بين هذه الحلول على ظروف الشبكة المحددة والإطار التنظيمي والموارد المالية المتاحة.

الكلمات المفتاحية: انسياب عكسي للقدرة الكهربائية الفائضة (RPF)، التوليد الموزع (DG)، انظمة الطاقة الشمسية (PV)، تأثير الانسياب العكسي للقدرة الكهربائية على الجهد، خسائر المحولات، استراتيجيات لتخفيف الانسياب العكسي للقدرة الكهربائية، نظام تخزين طاقة البطارية، ادارة احمال المستهلكين، أجهزة التصدير الصفرية،العاكسات الذكية.