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REACTIVE POWER COMPENSATION TECHNIQUES AND REPORTING IN ELECTRICAL NETWORKS

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THESIS ACCEPTANCE

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ABSTRACT

Integrating renewable energy sources into the modern grid has been challenging in terms of maintaining grid stability and quality. Changes in renewable energy production and fluctuating load demands have brought innovative methods for reactive power compensation. This thesis discusses some adaptive reactive power compensation algorithms for renewable energy integration and evaluates their effects on grid stability and efficiency.

The main purpose of this thesis is to present an adaptive reactive power compensation model that can dynamically adapt to changes in the grid. Advanced control algorithms that can provide maximum power quality are targeted with STATCOM, which is selected as the main compensation device. Within the scope of the research, the responses of STATCOM under active grid conditions and the innovations in the grid to which it is added at certain periods are investigated through simulation and calculation.

Adaptive control philosophy will be simulated using DIgSILENT to evaluate its performance by looking at basic values such as voltage sharpness, power factor optimization and energy efficiency, and necessary comparisons will be made and visuals will be provided with graphics. In addition, within the scope of this thesis, it will be investigated how a STATCOM can make a difference in performance compared to classical compensation devices in terms of its advantages in cases where renewable energy is of high importance.

The results obtained in all these stages show that the proposed adaptive control strategies significantly increase the stability of the grid, especially under sudden changes in renewable energy output. The important results obtained as a result of the thesis studies emphasize the importance of adding intelligent control systems to reactive power management for future electrical grids.

The innovative contributions in this thesis are threefold: comprehensive analysis of the limitations of conventional techniques, formulation of an adaptive algorithm specifically for renewable energy grids, and performance evaluation by proposing a framework for multiple scenarios. Furthermore, by investigating the possibility of reduced losses with a STATCOM-based system compared to conventional methods, this thesis further emphasizes energy efficiency.

The research conducted in this study provides valuable insights into adaptive reactive power compensation and its vital role in supporting the transition to sustainable energy systems. The proposed framework not only addresses the urgent challenges of renewable energy integration, but also lays a foundation for future work in the field of smart grid technologies and smart energy management systems. The current work bridges the gap between theoretical development and practical application by proposing a robust solution to improve grid stability in the renewable era.

CONTENTS

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
DC	Direct Current
AC	Alternating Current
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
RMS	Root Mean Squared
FACTS	Flexible AC Transmission
VAR	Volt-Amps-Reactive
HVDC	High Voltage Direct Current
DER	Distributed Energy Resource
PV	Photovoltaics
CBA	Cost-Benefit
VSC	Voltage Source Converter
BESS	Battery Energy Storage System
CBA	Cost-Benefit Analysis
COM	Control Module
TCR	Thyristor Controlled Reactor
TSC	Thyristor Switched Capacitor
FC	Fixed Capacitor
PCC	Point of Common

CHAPTER ONE

INTRODUCTION

1.1 Introduction

The global energy landscape is undergoing a fundamental transformation as renewable energy sources, such as solar and wind power, increasingly replace conventional fossil fuels. [37] This transition is driven by the need to mitigate climate change and reduce reliance on non-renewable energy sources. [38] The most technical difficulty of how to merge high tempos and instability of renewable energy into modern power grids is there. [39] These variations often lead to grid instability, voltage fluctuations, and power quality problems especially in systems with high renewable energy shares. To guarantee stability and reliability, advanced solutions are needed to integrate renewable energy into the power grid. Dealing with these challenges necessitates advanced management of reactive power, load variation and stability of the grid under dynamic condition. Among these countermeasures, adaptive reactive power balancing technology has proven to be an effective approach to address the potential negative impact that could arise from the variability of renewable energy sources. My thesis addresses the development and assessment of such techniques to improve grid performance and facilitate the effective integration of renewable energy sources. However, these not only improves the stability of the power grid but also helps in enhancing the energy efficiency as it reduces the losses in reactive power. It aims to add value to the existing industry or fundamental research with regards to energy systems and to develop solutions for modern grids with the integration of renewable energy.

1.2 Problem Statement

The global energy landscape is undergoing a fundamental transformation as renewable energy sources, such as solar and wind power, increasingly replace conventional fossil fuels. [37] This transition is driven by the need to mitigate climate change and reduce reliance on non-renewable energy sources. [38] The most technical difficulty of how to merge high tempos and instability of renewable energy into modern power grids is there. [39] These variations often lead to grid instability, voltage fluctuations, and power quality problems especially in systems with high renewable energy shares.

It is also possible to look the reactive power in order to maintain a constant voltage across the grid and therefore enable the transport of effective power. [40] Traditional compensation methods such as fixed capacitors and shunt reactors, are generally inept for this type of unpredictable and dynamic behavior presented by the renewable energy systems. the growing complexity of contemporary grids, with distributed generation and bidirectional power flow, requires more advanced and adaptive compensation strategies Although devices such as the STATCOM have been suitable tools for reactive power control, their performance mainly relies on the control strategies being used. Most existing reactive power compensation methods are often not sufficiently adaptive to effectively grasp the real-time dynamic shifts of load demand and renewable energy generation [41]. This highlights the necessity of advanced intelligent algorithms capable of dynamically balancing reactive power, enhancing grid stability, and providing optimal power quality in renewable energy-integrated grids. Principle Diagram of STATCOM The operational structure and working principles of STATCOM is illustrated in the principal diagram as shown in the Figure 1.1. As a shunt device, STATCOM can control the system voltage by absorbing or injecting reactive power.

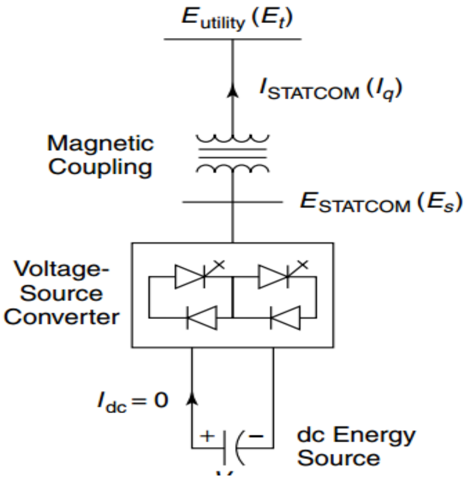


Figure 1. Principle diagram of STATCOM [59]

1.3 Definition of Terms

For a better comprehension of the terms discussed in this study, key terms provided here are defined as follows:

1. Reactive Power: The part of electricity that does no work but is needed to maintain voltage in the grid.
2. STATCOM: Static Synchronous Compensator, reactive power compensation device
3. Adaptive Control: A control methodology that dynamically updates system parameters to changing operating conditions in real-time.
4. Incorporating into the Grid Renewable Energy: Describes incorporating into the power grid energy created from renewable resources, like wind power and solar power.
5. Grid Formation: One of the mechanisms that generate and measure the stability of the grid.

1.4 Significance of the Study

There are several reasons this piece of research is important. This is of multifaced importance for the energy transition: firstly, it tackles a crucial challenge for the energy transition worldwide, which is how to keep the grid stable as more and more renewable energy is integrated. This work aims to contribute to the body of knowledge in this area by developing reactive power allocations that can adapt to observed dynamics in transmission grids.

Second, this research is useful in the smart grid field since it introduces intelligent control systems into reactive power provision problems. The offered remedy adds an improved Operational efficiency to STATCOM Devices and gives a scalable basis for future energy systems that are anticipated to witness high stages of renewable strength penetration.

Thirdly, this study brings a practical aspect for grid operators, policy makers and renewable energy developers. These solutions can reduce operational expenses, lower energy losses and improve power system reliability by stabilizing the grid and control power quality. This, in turn, underpins the larger imperative to shift to sustainable and resilient energy systems.

Finally, this research contributes to the global fight against climate change by facilitating renewable energy integration into power grids of different countries. The objectives of this research contribute to better understanding of the policy decision of interest, and can thereby help to inform the technical standards which ensure the quality of these clean energy technologies to encourage their adoption.

1.5 Limitations of the Study

Although it contributes to the evidence base, this research has a number of limitations that must be recognized.

1. Adaptive Control Strategy through MATLAB Simulink: These tools allow for easy comparison of PV and their impact on the power system, but they do not account for unforeseen grid events and environmental factors that occur in real-world power systems.
2. Concentration on STATCOM: The research only emphasis on STATCOM as the emotion power compensation instrument. This will typically use a solution based on a static synchronous compensator.
3. Focus on Renewable Energy Scenarios: The paper looks at specific scenarios for wind and solar renewable energy integration scenarios. These outcomes may not directly transfer to other renewable energy systems.
4. These proposed algorithms are intended to be scalable for larger power systems, however considering the costs associated, regulatory compliance, and integration with current infrastructure must also be considered when implementing the solution on larger scales.

The study, by acknowledging these shortcomings, lays groundwork for future studies dedicated to overcoming these obstacles and contributing to the further enhance adaptive reactive power regulation technology.

Ultimately, this premise establishes the relevant nature of our study on the importance of adaptive reactive power balancing algorithms for renewable integration. Through establishing the problem statement, defining important terms, justifying the importance of the study, and addressing the limitations of the research, this chapter provides a thorough background for the study being conducted in next chapters.

CHAPTER TWO

REVIEW Of THE LITERATURE

2.1 Theoretical Background of Reactive Power Compensation:

To improve efficiency, stability, and reliability of power systems, reactive power compensation has an essential role in modern electrical networks [1]. Reactive power is defined as the power wasted due to inductive loads, while real power is defined as the power actually used by the load. We can easily calculate apparent power as the products of the RMS values of voltage and current. P. F=Real Power (Watts)/ Apparent Power (VA) (or) Power Factor is a ratio of real power to apparent power. In order to raise the power factor, this reactive power must be reduced; this can generally be accomplished in the form of connecting capacitors in parallel with the load, static VAR compensators, synchronous condensers, or other assorted electronic circuits. [2]. With the increasing complexity of electrical networks, power management of reactive power has gained importance [3]. The power exchange in a transmission line in both active and reactive forms is shown in Figure 2.1 The direction of the arrow indicates the direction of the flow. Unlike active power, Reactive power does not contribute to net energy transfer [4].

Reactive power is important because it helps address problems of voltage instability, power losses, and inefficiency due to poor power transmission and distribution [5]. Static capacitors and reactors are simpler and cheaper; hence, the choice of this type of static compensation method has been extensively made [6]. Alongside the traditional solution, in some applications, such as the application environments with many dynamic loads, high-technology power electronics have efficiently provided dynamic responses by employing the dynamic power factor compensators (SVC, STATCOM) [7]. The basic concepts of reactive power compensation consist of highly complex mathematical models that analyze, forecast, and control the behavior of reactive power within a given network [8]. These models are useful in designing compensation strategies to maintain voltage at the optimal value and minimize losses [9]. This literature review is divided into three parts: reactive power compensation techniques, theoretical background and importance of reactive power compensation, and economic analysis of reactive power compensation. The findings presented in each chapter summarize the essence of the foundational documents to facilitate the knowledge and rationale for research and application in the field of reactive compensation in electrical engineering.

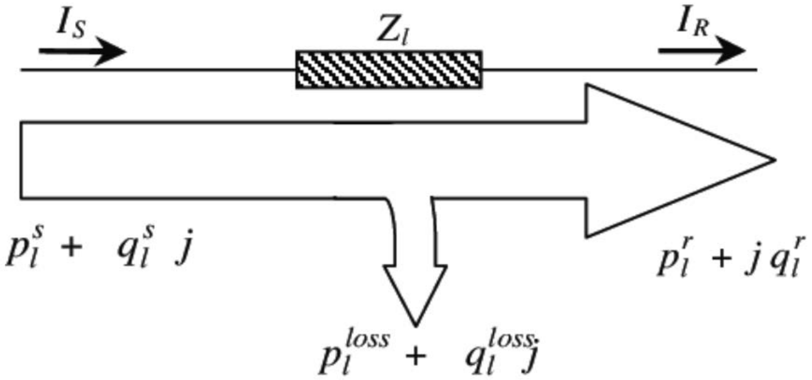


Figure 2.1. Reactive power flow in a power system [31]

2.1.1 Mathematical modeling of reactive power:

With the increasing power demand, it has become necessary to develop models that explain the temporary characteristics of reactive power to cover the entire electrical network. [12]. Typically, power models consist of complicated differential equations that describe the relationship between voltage, current and reactive power [13]. In order to develop effective compensation schemes and to predict system performance at various operating points, accurate modeling has to be conducted [14].

2.1.2 Voltage Stability and Reactive Power:

Voltage Stability is one of the most critical concepts to know the reactive power Compensation [15]. Voltage instability has been identified as the source for the severe operating issues - voltage sag and oscillatory/non-oscillatory power outage problem [16]. To prevent this situation, providing or absorbing the necessary reactive power helps keep the voltage within specified limits against the necessary dynamic voltage transients. [17].

2.1.3 Impact on Power Quality:

Voltage Regulation and power factors are the examples of devices that directly intervene in the power quality changing the VAR to regulate the current flow in the network [18]. The reactive power compensation is necessary for enhancing the power quality, and even for the safe and effective running of the electrical grid [19].

2.1.4 Compensation Technologies and Equipment:

Various technologies and equipment deployed for reactive compensation are available with different pros and cons [20]. SVCs and STATCOMs are the most powerful systems for fast adjustment to sudden events and effective reactive power compensation [21]. Figure 2.2 shows the basic circuit configuration of the SVC connected at the terminals of the wind farm. Other types of commonly used compensation devices are capacitance banks; But despite the simplicity and low cost they are inferior to SVCs because they can only offer capacitive support which is of limited use. [22].

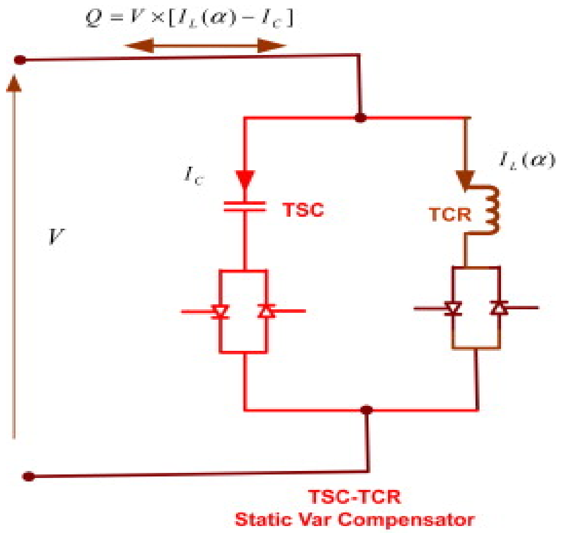


Figure 2.2. SVC basic configuration circuit [32]

2.1.5 Control strategies for reactive power compensation:

The performance of reactive power compensation systems depends a lot on the control strategies. Compensation devices performance is very satisfactory with using the advanced control algorithms like Fuzzy logic, neural networks and adaptive control techniques [23]. These basically are commonly been developed for optimal strategies that allow the power system to react against variable load conditions roll to performing the best system state [24].

2.2 Reactive Power Compensation Techniques:

2.2.1 Overview of Reactive Power Compensation Methods:

Static and Dynamic reactive power compensation techniques can be defined as two different concepts. Some static compensation techniques, especially fixed capacitors and reactors, are quite simple and inexpensive [25]. However, dynamic compensations offer dynamic and fast reactive power control using modern power electronic devices. where the most common technologies are SVCs and STATCOMs [26].

2.2.2 Static Compensation Methods:

Static capacitors (reactive compensation) are largely applicable to supply leading reactive power restorative devices, thereby increasing the power factor and alleviating the voltage profile of the system [23]. Capacitor banks are low-cost and quick to install, which makes them a solution commonly used in many applications. Reactors that help absorb excess reactive power are crucial in systems with high inductive load levels. A Typical SVC Compensator diagram is shown in Figure 2.3 However, in dynamic environments, where load status changes rapidly, static methods show low responsiveness and flexibility [21].

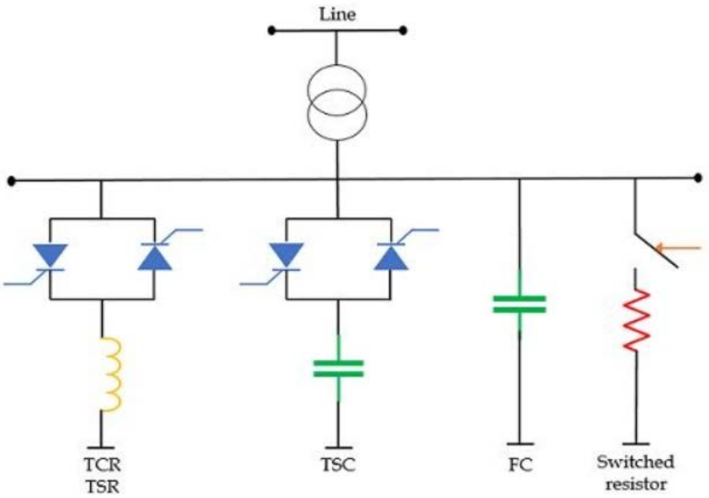


Figure 2.3. Static VAR compensator [33]

2.2.3 Dynamic Compensation Methods:

SVCs and STATCOMs Dynamic compensation methods have made power quality become a matter of course since the rise of power electronics. Since the 1950s, SVCs are based on thyristor-controlled reactors and capacitors and provide both real-time and fast reactive power compensation and are therefore well suited for applications requiring rapid reaction onto changes in voltage [24]. A Typical SVC configuration and V/I diagram are shown in Figure 2.4 STATCOMs with voltage-source converters also provide a shortened response time and high flexibility in reactive power control, which are significant for RTSs and grid connection control for non-dispatchable RE sources with fluctuating power outputs [27].

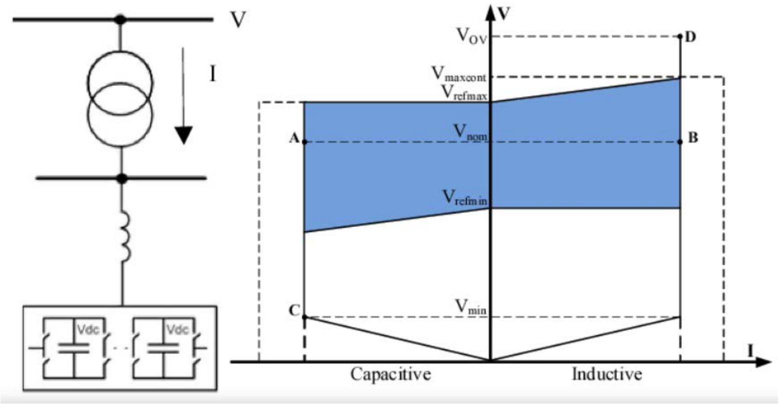


Figure 2.4. Typical STATCOM configuration and V/I diagram [34]

2.2.4 Hybrid Compensation Methods:

These methods Combine Static and Dynamic elements to utilize strengths and weaknesses. Fixed capacitors, reactors, and advanced power electronic devices control reactive power outputs completely. A Typical Hybrid STATCOM V/I diagram is shown in Figure 2.5 Hybrid systems can favor the most cost-efficient technologies while preserving the adaptability and real-time response needed for modern power systems [28].

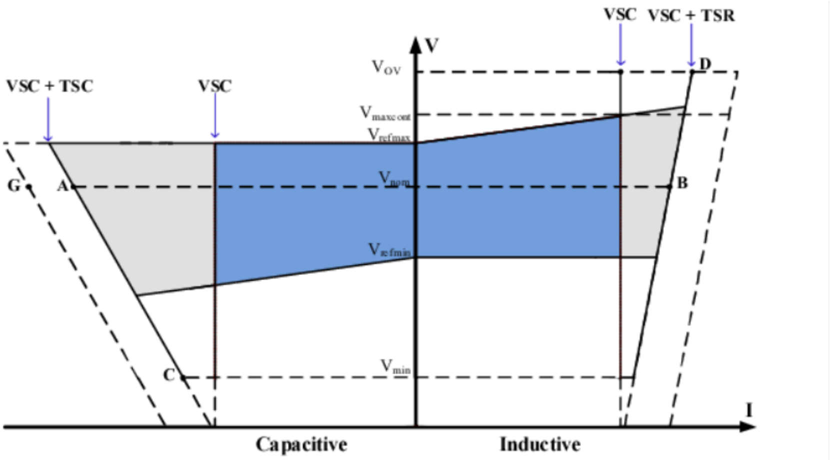


Figure 2.5. Hybrid STATCOM V/I diagram [35]

2.2.5 Practical Implementations and Case Studies:

It may have numerous applications in various industrial applications, and numerous case studies illustrate the practical side of implementing reactive power compensation techniques. For example, installing an SVC system has improved voltage stability and power factor correction in a large industrial plant. [29]. Through the use of STATCOMs in another case study, it was found that these devices can stabilize the voltage of wind farms with fluctuating renewable energy power output [30].

2.3 Economic Analysis of Reactive Power Compensation

2.3.1 Economic Impact on Power Systems:

The economic impact of reactive power compensation is considerable, affecting operations costs and long-term financial planning [10]. A properly designed and located compensation compensates the power losses by reducing the line current, Leading the load current to improve the system's voltage stability and overall performance [11]. Cost-benefit analysis (CBA) for most of the compensation devices reveals that the financial savings from efficiency and maintenance savings are paid back quickly compared to the towers under use [4].

2.3.2 Cost-Benefit Analysis of Compensation Methods:

Reactive power compensation methods and their tradeoffs are provided in detail with a formal cost-benefit of these technologies [5]. Figure 2.6 shows that after compensation, the phase angle difference between current and voltage decreases, and the power factor increases. This process can meet the tracking requirements of the power system for reactive power compensation and eliminate the penalties caused by low power factor. Though static methods are cheap, operational costs could be higher due to less flexibility offered [6]. While dynamic means are generally more expensive initially, they usually save more in the long term by increasing system efficiency and decreasing power losses [7].

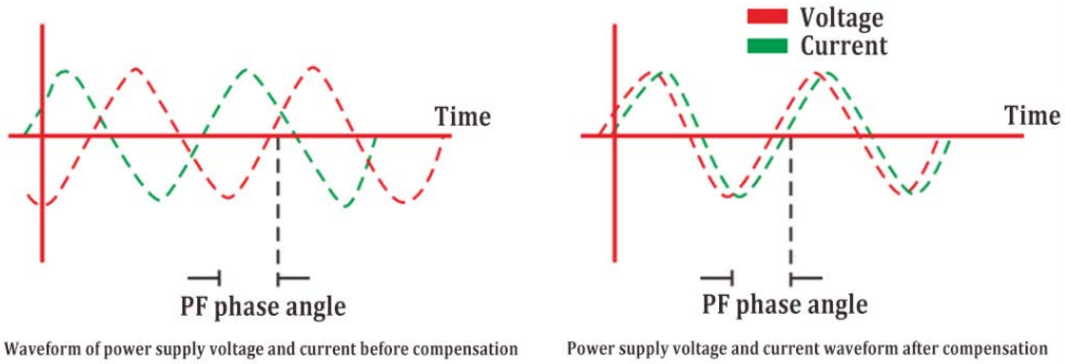


Figure 2.6 Schematic diagram of compensation principle [36]

2.3.3 Evolution of Compensation Techniques:

Reactive Power Compensation Techniques Over the past few years, practical reactive power compensation techniques have undergone a great evolution due to technological changes and the increasing load demand in power networks [5]. Older methods mainly depended on using fixed capacitors and reactors, but with the advance of the technology more sophisticated power electronics based solutions are being use to provide dynamic and flexible compensation [6].The maturation of FACTS (Flexible AC Transmission Systems) and HVDC (High Voltage Direct Current) technologies of recent decades has both broadened the capabilities available for damping system oscillations and facilitated significant efficiency and reliability improvement in power delivery [7].

2.3.4 Comparative Analysis of Different Methods:

Comparative analysis of the different methods of reactive power compensation shows the strengths and weaknesses of various reactive power [8]. Nevertheless, static methods tend to be both cheaper and easier to implement than dynamic ones, but they do not have the responsiveness that is required in the dynamic environment [9]. Though dynamic devices like SVCs and STATCOMs offer much better performance in terms of voltage stability and the control of reactive power fluctuations, the cost and complexity of these devices are higher [10]. In order to choose the most adequate compensation method, there must be in-depth knowledge of the system requirements and states as a whole [11].

2.3.5 Future Trends and Innovations:

The future of reactive power compensation depends on the evolution of improved technologies and new ideas [27]. Some trends can also be seen with the use of renewable energy sources, smart grid technologies, and the development of new efficient and cost-effective power electronic devices [28]. Recent research and development efforts endeavor to build systems capable of adjusting to the changing spectrum of power systems, guaranteeing infallible and productive operation amidst overall escalation and demand in the environment of perpetually increasing system intricacy [29].

CHAPTER THREE

METHODOLOGY

3.1 Study Region: Kurdamir City

This thesis presents a quantitative, simulation-based research design in order to analyze and validate various adaptive reactive power compensation algorithms in the context of the integration of renewable energy systems. The quantitative approach is useful in this research, enabling the precise measurement and evaluation of variables such as reactive power level, voltage stability, and power factor correction across operational scenarios. [42] The methodology melts theoretical modeling and practical simulation tools within a unique methodology framework that is both accurate and applicable in real-world applications.
The study focuses on the representative case study of the city district of Kurdamir. Focusing on this district, the research will provide applicable insights into the management of reactive power in regions with increasing penetration of distributed generation. In order to reach its goals, first, some theoretical models about different reactive power compensation methods have been worked out for this study. The development of these models is based on the established electrical engineering principles adapted to deal with specific features of renewable energy development. With different operating conditions and different control strategies, how well individual devices achieve reactive power balance. The main results of using this technology are a significant reduction in reactive power flows and greatly improved voltage regulation. STATCOM Compared with conventional compensation devices, its reactive power compensation function is quite flexible.

Thereafter, the accuracy of these models has been verified by simulating grid operation using up-to-date digital technologies such as MATLAB/Simulink and DIgSILENT a program to digitally describe the set of grid operations. These tools make it possible for us to create all kinds of scenarios, from peak operation state to renewable energy saturation when prices remain unlimited, fault operation condition and so on are studied.

Thus, this research examines the ability of adaptive reactive power balancing techniques to assure acceptable voltage limits, lessen system losses, and enhance power quality.The simulation outputs are contrasted with benchmark results from similar arrangements and validated through standard performance metrics (voltage deviation, total harmonic distortion, and reactive power compensation efficiency). This ensures that the results will not only be robust, but generalizable to other areas with similar energy profiles. We aim to connect theory and practice through a research design in which theoretical modeling is complemented by simulation-based validation. This duality of accuracy and applicability reinforces the commitment of the study to solutions that are not only technically correct but can also be put into practice.The recommendations from the Kurdamir case study will be used to lay the foundation of guidelines for proper reactive power management in regions asivelas facing the same challenges.The mountainous region of Kurdamir in central Azerbaijan lies on key energy transmission routes in the Aran region and serves as a connection point in the national electricity infrastructure. Occupying a vast area with a semiarid climate, the area features strong seasonal swings, with hot summers and cold winters. [43] These weather patterns strongly influence energy demand, which sees distinct peaks during extreme (i.e. hot and cold) weather seasons. Summer peaks in electricity demand are mainly caused by the use of cooling systems, whereas winter peaks are driven by heating demand.

The geographical location of the region also makes it a critical area for the integration of renewable energy. Kurdamir is situated in close proximity to solar farms with extensive sunshine exposure and wind farms in the surrounding high-wind potential sections, and therefore, the district can take advantage of renewable energy production facilities. However, the use of these renewable energy sources presents challenges associated with voltage stability, reactive power balancing, and grid reliability due to their inherent variability/ intermittency, although they do contribute to the region’s energy mix. [44] Moreover, Kurdamir's location within Azerbaijan's energy grid means that it falls along several of the most important energy transmission corridors. This strategic positioning guarantees its role as the regional energy distribution pool and points at its appropriateness as the study area to evaluate the impact of renewable on a reactive power management. The addition of renewable energy into the Kurdamir grid not only satisfies local energy demand but also influence on the stability and efficiency of the power grid as a whole.

Beyond its energy traits, Kurdamir's semi-urban demographic features of inhabitants such as the energy consumption pattern add to the diversity of energy requirements. The consumers in this space include residential, commercial, and agricultural, among others. Such versatility offers a specific opportunity to evaluate the impact of reactive power by compensation techniques on various consumer levels of load as well as nature of consumption. Agricultural irrigation systems, often also seasonal, introduce yet another layer of complexity in the grid’s reactive power needs. Kurdamir is evolving purely from a developmental standpoint to modernize its electricity infrastructure.

In line with Azerbaijan’s wider efforts toward renewable energy adoption and grid modernization, the region is progressively investing in high-tech features like distributed energy resources (DERs) and smart grid systems. It is a perfect candidate for the study of such advanced re-active power compensation methods and assess their effectiveness in real-world environment. In conclusion, justifying why Kurdamir will serve as an excellent case study for this research, both on the unique mix of geographic, climatic, and infrastructural characteristics. Due to its closeness to renewable power sources, coupling with major power transmission lines, and variety of energy utilization types, it is an essential section for the study and optimization of reactive power flow in the electrical network. The insights you gain from this study could potentially lead to national roadmap for the integration of renewable energy without compromising the stability and reliability of the grid.

3.1.1 General Power Loading Characteristics

As a result of the interaction between the residential, commercial and agricultural sectors, there is a diverse and dynamic power consumption profile of Kurdamir City. Each sector provides unique contributions to the overall loading profile, which also varies with seasonal variations, economic activities and renewable energy integration. [45] Peak demand periods in the city mainly happen during summer afternoons and winter evenings. During peak summer, the rural and semi-urban areas consume electricity through large agricultural irrigation systems, while in residential and commercial zones, high-temperature days create demand for air conditioning. In winter, heating loads are the main contributor to evening peaks while the ambient reduction in daylight hours increases lighting demand. These fluctuations are a challenge to the local gird, which struggles to preserve voltage stability and minimize losses.

Peak energy demand and variability of renewable energy sources make voltage stability and reactive power management ever more critical. Requirement of reactive power enhances during the peak load period as a result of increased inductive loads (AC, industrial equipment, etc.) which cause voltage sag and higher line losses if not properly compensated . Additionally, during periods of high solar irradiance or strong winds, renewable energy output may dominate, resulting in overvoltages occurring at certain locations in the grid. However, due to its intermittency, these sources need to vary reactive power compensation to stabilize the voltage frequently. [46] The consistency in the peak load demand juxtaposed with renewable energy instabilities calls for reactive power compensating solutions like capacitor banks, STATCOMs, and dynamic voltage regulators to ensure grid stability. Will be highly dependent on the electrical infrastructure modernization and smart grid technologies adoption. Peak shifts, coupled with advanced compensation systems and energy efficiency measures, will harmonize demands and results from quartz and other renewable energy sources, moving the city closer to a desired energy objective.

3.1.2. Renewable Energy Potential in Kurdamir City

Kurdamir City, located in Central Azerbaijan, has a dry subtropical climate with hot summers, warm to cool winters and low rainfall. Such climatic conditions make the region very suitable for the implementation of a PV system to effectively use the abundant solar energy of the region. In this context, Kurdamir can increase its power supply through renewable means by taking advantage of its climatic and geographical advantages.

Favorable Climate Features for Solar Energy:
Summers in the region are rainless, while winters are rainier. Annual rainfall varies between 430 mm and 185 mm. Relative air humidity varies between 50%-60% in summer and 75%-80% in winter. The average temperature in January is 4.6 °C, while it rises to 28 °C in July, and the annual average temperature is 15.8 °C. In fact, the maximum temperature recorded in Kurdamir was 44 °C, indicating that the region has long-term and high-intensity solar radiation. These conditions also match the operational requirements of PV systems, as extended sun hours in the summer months can support significant solar energy production.

Solar Energy as a Primary Focus:
Kurdamir receives an average of 4.5-5.5 kWh/m²/day of solar radiation with approximately 280-300 sunny days per year, making it one of the most suitable regions for solar energy production in Azerbaijan. [47] Its flat terrain and the availability of underutilized land are conducive to the development of large-scale solar farms. Additionally, rooftop solar installations on residential and commercial buildings offer decentralized energy solutions that reduce grid strain. However, the efficiency of PV modules can decrease due to high summer temperatures. To counter this, high-tech PV technologies such as temperature-resistant materials, double-sided panels, and cooling systems are required to achieve maximum energy output in extreme temperature conditions. The inclusion of solar tracking mechanisms can also increase efficiency by maximizing solar exposure throughout the day.

Advantages of Solar PV Systems for Kurdamir:

1. Peak Demand Alignment: Peak temperatures coincide with peak electricity demands for cooling, a need directly met by solar PV systems, reducing dependency on traditional energy sources.
2. Cost Effectiveness: Due to the ever-decreasing cost of PV technologies and the rich resource base, Kurdamir is in a position to realize significant economic benefits through solar energy.
3. Scalability: Solar PV systems can be flexibly deployed from small-scale rooftop units to large-scale farms, meeting a variety of energy needs.
4. Environmental Impact: Adopting solar energy significantly reduces carbon emissions, thus aligning with national and global sustainability goals.

Infrastructure Supporting Solar Integration:
The full potential of solar energy can only be realized by upgrading Kurdamir's grid infrastructure. [48] BESS will help store excess energy generated during sunny days for use at night or on cloudy days, ensuring continuous supply. Advanced grid technologies such as STATCOM are essential to increase the grid's capacity to integrate renewable energy, reducing voltage fluctuations and reactive power imbalances.

Other Renewable Energy Sources:
While solar energy is the leading renewable focus for Kurdamir, there is more potential from biomass energy from agricultural waste. On the other hand, wind energy in this region cannot offer large-scale projects due to low average wind speeds (5-6 m/s) - hydro and geothermal resources are also negligible.

3.2 Methodology for System Modeling

The quality of the collected data and the robustness of the input parameters are vital for the reliability and accuracy of the system modeling. This research adopts comprehensive data collection to gain in-depth knowledge of the Kurdamir City power grid: its structure, operation, and dynamics. The data is collected from various sources such as the local grid operator, utilities, historical records, and technical documentation to represent the system holistically. [49]

The data sources for this study are the local grid operators and utilities data. These provide critical operational insights into the power grid such as the network topology and layout, which define the configuration of transmission and distribution lines. Real-time and historical power flow data indicate the changes in active and reactive power at different nodes. In addition, the technical specifications and capacities of existing reactive power compensation equipment such as capacitor banks and transformers are also taken into account. These basic data will facilitate the creation of a digital twin of the Kurdamir grid for high-fidelity simulation and analysis of system dynamics.

Historical Load and Generation Data: Useful for learning seasonal and temporal changes in power demand and generation. In the study, critical load peak demands in different seasons such as summer afternoons or winter evenings are observed based on hourly and daily collection. Renewable generation sources including photovoltaics and wind power outputs are provided to highlight the variability and intermittency that greatly affect regional reactive power concerns. Furthermore, historical voltage sags, overvoltages and system losses increase the realism and validity of simulated scenarios such as peak load conditions and fluctuations of renewable energy, providing greater insight into areas where targeted interventions will be required.

Network Component Properties: To ensure that the behavior of the electrical network is well modeled, a precise collection of the essential properties of the network components is performed. Transformers will be analyzed for their ratings, impedance values, and tap-changing capabilities that affect voltage regulation and reactive power flow. The performance of STATCOM devices is evaluated with respect to parameters related to their reactive power capabilities, response times, and operating limits to assess their actual performance. Capacitor banks are usually characterized with respect to their capacitance, operating voltage, and switching mechanisms to understand the contribution of such a bank to the reactive power balance. Distribution Lines and Cables can be checked for resistance, reactance, and length to simulate power losses and voltage drops across the network.

Additional data sources: In case of local data gaps, additional data sources such as regional energy authorities, government reports and public databases provide further information on long-term renewable energy integration plans for Kurdamir and its surroundings. [50] The regulatory framework includes compliance requirements for reactive power compensation. Such future projections of load growth and renewable energy penetration enhance the forward-looking perspective of the study by facilitating scenario modelling for the projected grid conditions.

Data Validation: This is an important step for the integrity of the collected data. The study cross-checks information from various sources to minimize errors and inconsistencies, thereby increasing the reliability of the system model. Such precisely calculated verification methods ensure that all input values correctly understand the complexities of the Kurdamir power grid.The dynamic performance of STATCOM in maintaining voltage stability with a nonlinear control strategy is discussed here.These new control algorithms are an improvement over traditional liner controllers, offering better processing speed when dealing with disturbances from the grid or changes in load.The control rule for quick voltage regulation can be expressed as in equation 3.1.

$$u = -k_1\left(V_{ref} - V_{PCC}\right) - k_2 \int \left(V_{ref} - V_{PCC}\right)dt \quad (3.1)$$

Non-Linear control calculations dynamically adjust the STATCOM's reactive power output values to maintain voltage stability.

k1: $(V_{ref} - V_{PCC})$- It takes into account the voltage error and provides corrective action by making immediate intervention.

k2: $\int(V_{ref} - V_{PCC})$ dt- It ensures long-term voltage stability and continuity by taking into account the errors and faults in the system archive.

This approach allows multiple data sources to be integrated sharing detailed technical parameters providing a strong basis for accurate simulations and reliable analyses of reactive power compensation strategies. As a result, the modelling is realistic and the data collection process allows for practical insights into the challenges and opportunities of reactive power solutions in Kurdamir City.

3.2.1 DIgSILENT PowerFactory

DIgSILENT PowerFactory is one of the most feature-rich and powerful tools available for analysis, simulation and optimization of electrical power systems. [51] Familiar with academia and industry, this functional tool is designed to study complicated electricity grids, running operational performance assessment and solutions for reforming systems to better energy stability and sustainability. Moreover, with the introduction up renewable resources its one o0f the better options to study modern power systems, with the addition of the capabilities of load flow analysis, fault analysis, transient stability and optimization.

This thesis presents the power grid analysis of Kurdamir City performed in DIgSILENT PowerFactory. The growing reliance on renewable energy sources, including wind and solar power generation, has introduced prominent voltage stability and reactive power management issues in this region. By modeling these detailed grid configurations and simulating various operational scenarios, the software ensures that the proposed solutions are not only realistic but also robust, customized to the unique requirements of the Kurdamir power grid. [52]

The relevant applications of DIgSILENT PowerFactory in this work include the following:

1. Kurdamir City Electricity Grid Modeling: This is a high-resolution digital replica of Kurdamir's electric grid including all necessary details like the load spread throughout this network or similar parameters for renewable energy levels and reactive power demand. The implementation of DERs and the modeling of their impacts on grid performance are important subjects and are also covered in the book. DIgSILENT PowerFactory reliably reflects the characteristics of the grid and thus detects possible weaknesses in the system such as areas with voltage sag or reactive power imbalance.

2. Load Flow Analysis One of the significant features of DIgSILENT PowerFactory is the load flow analysis; in this study, load flow analysis is used to analyze power flow in the Kurdamir grid in different operating conditions. It will also give insight into the system's active and reactive power demand, voltage profiles and line losses. The main aids in recognizing instances that need reactive power compensation to ensure optimum performance and meet voltage constraints. The load flow results can also guide the placement and sizing of compensation devices (such as capacitor banks and STATCOMs).

3. Grid Stability Testing: There is a fundamental challenge to integrating regenerate energy sources, which is the variability and intermittent nature of their outputs. The impact of such fluctuations on grid stability is simulated by DIgSILENT PowerFactory. The software studies things like drops in wind generation and rapid changes in solar output to see how these scenarios can impact voltage levels, power factor and general grid performance. The simulations will enable to check the ability of the proposed adaptive reactive power compensation algorithms in stabilization of the system

4. Reactive Power Optimization: To steady-state analysis, the software will also enable the study of dynamic, and transient behavior in the simulation of faults, load interruptions, and equipment outages on the grid to study aspects of grid resilience and response.

5. Dynamic and Transient Analysis: In addition to steady-state analysis, the software will allow the study of dynamic and transient behavior in the simulation of faults, load

interruptions, and equipment outages on the grid to examine grid resilience and response. The outcome of such simulations will provide further insight into how reactive power compensation can help increase the reliability of a system during extreme contingencies.

In this context, the integration of DIgSILENT PowerFactory in this study demonstrates its value for comprehensive and reliable solutions to modern power system challenges. The possibility of combining advanced analytical capabilities with practical simulation makes the findings theoretically sound and operationally applicable. Utilizing this software, the study not only assesses the current status of the Kurdamir power grid, but also suggests applicable solutions to improve reactive power management in the face of increasing renewable energy adoption.

3.2.2 Grid Modeling in DIgSILENT

DIgSILENT PowerFactory, a very modern software tool that enables simulation, analysis and optimization of electrical networks, will be used to model the electrical network of Kurdamir City. The modeled network should allow a general virtual representation of the existing network, considering only some important parameters and configurations representing the specific energy profile of the city. In modern power systems, optimization of reactive power compensation is crucial for maintaining grid stability and reducing loss. It has an effect on the utilisation rate (for lost power), reliability of service for load users who need constant So too does the efficiency within a network; anything that adds to congestion or closes routes through which energy can flow results in greater average power losses across capacitor banks and worse Q-factors unify over all conductors which help restrict line heating Competent reactive management means making use of devices like STATCOMs and installation techniques such as capacitors at the right points in order to cater for reactive power harmonics produced by customer loads. This provides a detailed expression for the reactive power compensation mathematical optimization model which can be stated in the following equation 3.2.

$$\text{Minimize } \sum_{i=1}^{N}(Q_i^2 * C_i) \qquad (3.2)$$

Q_i^2: Reactive power supplied or absorbed by the i-th compensation device(MVAR)
C_i: Cost coefficient associated with the i-th compensation device
N: Total number of Compensation devices

This model provides a basic platform to conduct the effectiveness study of various compensation techniques in different states and situations, integrating detailed load profiles with various reactive power compensation devices together with renewable energy sources. Figure 3.1 shows a general representation of the smart grid model developed in DIgSILENT PowerFactory and shows the integration of different renewable energy sources such as wind farms, solar farms, biogas plants and energy storage systems. It includes basic elements such as total load demand divided into contributions such as transformers, external grid connections and plug-and-play electric vehicles. DigSILENT PowerFactory system modeling can simulate a large system to obtain files with access to simultaneous treatment organization according to red launch systems. [53] It provides a conceptual view to understand the basic ideas of compensation techniques and grid modelling, which are fundamental for system performance analysis.

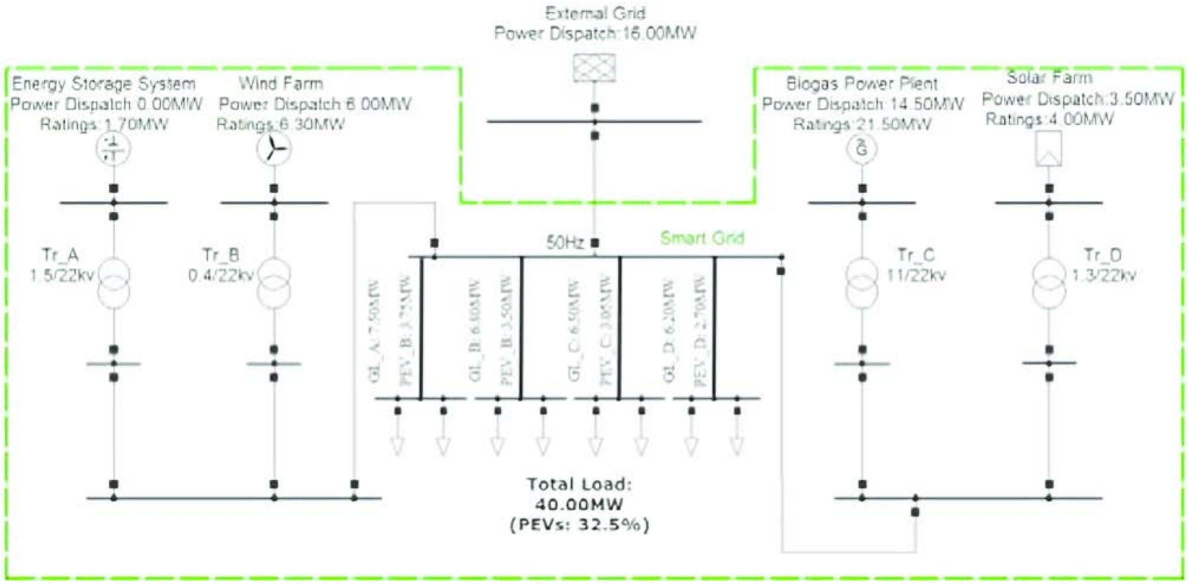


Figure 3.1. DIgSILENT PowerFactory for the smart grid study system [60]

Detailed load profiles of the residential, commercial and agricultural sectors are included in the network model representing energy consumption patterns. Residential loads refer to household appliances, lighting and HVAC systems. Demand peaks in summer afternoons and winter evenings. Commercial loads represent the energy used by businesses and public facilities, which are mostly focused on business hours and feed a significant part of the daytime energy demand in the city. Agricultural loads, characterized by seasonal irrigation systems driven by large motor pumps, show the highest consumption during the summer growing season and impose significant reactive power requirements due to their inductive nature. Hence, these time-based load profiles allow the model to replicate real-world operating scenarios and identify the important nodes that need reactive power support

Advanced and traditional compensation devices, including STATCOMs and capacitor banks, are included in the model to address reactive power challenges. [53] STATCOMs are highly sensitive devices that are modeled in great detail by specifying their reactive power capacity, response time and control settings so that their performance can be evaluated under changing grid conditions. In electric power systems where transient events such as sudden changes in load, grid failures or renewable energy inputs occur, the problem is how to maintain voltage stability. As a FACTS device, the STATCOM is very helpful in mitigating these transient effects by absorbing or injecting reactive power. The main part of this analysis deals with the energy balance in the DC link capacitor of a STATCOM, as indicated in equation 3.3.

$$E_{dc} = \frac{1}{2} C_{dc} V_{dc}^2 \qquad (3.3)$$

E_{dc}: Energy stored in the DC-link capacitor (J),
C_{dc}: Capacitance of the DC-link capacitor (F)
V_{dc}: Voltage across the DC-link capacitor (V).

This equation highlights the role of the capacitor in maintaining the DC breakdown voltage during transients. In responding to sudden demands for reactive power from one moment to the next, the DC link capacitor of the STATCOM must now transmit or receive energy to maintain stable levels in the bus load (PCC). Traditional compensation methods, namely capacitor banks, are included with their nominal capacities, operating voltages and switching mechanisms to evaluate their effectiveness in steady-state reactive power support and power factor improvement. It will offer a full comparison of these apparatus in voltage stability and compensation of reactive power.

The DIgSILENT model is built to run dynamic and steady-state scenarios to understand behavior of grid. Dynamic analysis focus on the network response to instantaneous changes like output variations of renewable energy, load variations and fault situations, which highlights the performance aspect of the STATCOM during dynamic events. Steady-state analysis measures the operational effectiveness of the network in the long term, for example load flow studies can be used to find areas that require high amounts of reactive power and voltage drop, allowing the application of the compensation devices in the right place.

Real-world operational data of the Kurdamir City power grid (load, generation, and characteristics of grid components) are used to validate the accuracy of the network model. Some of them are voltage profiles, power losses and the reactive power flows, which are compared with the actual ones to validate the reliability of the simulations. The model can shed light on important cases such as high renewable energy penetration, seasonally peaking load conditions and the individual impact of STATCOMs and capacitor banks on reactive power compensation efficiency.

In summary, the DIgSILENT PowerFactory model provides a comprehensive analysis of reactive power management strategies in the core grid of Kurdamir City with respect to various objectives. It simulates real world scenarios and corroborates its results with operational data, offering a validating perspective on how the city could enhance the stability,

3.2.3 Simulation in MATLAB Simulink

MATLAB Simulink environment can be used for the development, implementation, and analysis of adaptive reactive power compensation strategies. [54] It employs very flexible and sensitive vehicle dynamic systems, which are then appraised to advanced control strategies, which ensures that the designed algorithms could be applicable in theory and praxis. Utilizing the modeling capabilities of MATLAB Simulink, the framework lays a strong performance analysis foundation for the reactive power compensation methods under different conditions.

Important aspects of this simulation framework are the implementation of detailed STATCOM models for the investigation of Statical Synchronous Compensators responding under different behaviours. The phasor models express steady-state behavior and power flows enabling fast simulations throughout the grid. In the phasor model the best solution is the simple way to study the steady-state behavior of a STATCOM in the power system. [53] Herein, the STATCOM is simulated as a voltage source with series impedance controllable. Thus, this phasor model can simplify and improve the studying of power flow and voltage regulation. This model captures the rapid dynamic behavior of the STATCOM and also its ability to compensate the reactive power while keeping a particular bus voltage value constant under variable conditions.

Due to its computational efficiency, the phasor model is mostly fit for large-scale power system studies. The steady-state model accurately captures the basic interactions of the STATCOM with the grid and allows for the fast simulation of a vast number of scenarios:

load changes, faults, renewable energy variability, etc. In this sense, the phasor model gives an insight of overall system performances through voltage profile, reactive power flow and grid stability measurement analysis.

A phasor model of the STATCOM has been developed in the MATLAB Simulink environment to be used for grid voltage regulation and reactive power compensation simulation studies. Using a phasor model the state variables and the control design of a STATCOM are analysed. In the power grid, when appropriate voltage is required the STATCOM can also inject or absorb reactive power accordingly, so as to maintain good power quality and help the grid run more smoothly.Quoted below with changes made for convenience is an epitaxial reactive power control having very clear relationship between control algorithm design and power semiconductors.he reactive power variation at the common connection point (PCC) between the STATCOM and the grid is governed by the equation given in equation 3.4 below.

$$Q = V_{PCC} * (V_{STATCOM} * \sin(\delta))/\mathrm{X} \qquad (3.4)$$

Q- Reactive power injected or absorbed by the STATCOM
$V_{STATCOM}$- Internal voltage of the STATCOM
V_{PCC}- Voltage at the point of common coupling
δ- Phase angle difference between
X- Impedance of the line connecting the STATCOM to the grid

This equation shows the connection between the STATCOM and the grid in terms of reactive power:
$\delta < 0$ the STATCOM injects reactive power into the grid, boosting voltage levels.
$\delta > 0$ the STATCOM absorbs reactive power, reducing grid voltage

proper dynamics of reactive power output is also established using a simple nonlinear dynamical system, represented by a sigma neural model, that allows adaptive control strategies to function in real-time by updating voltage setpoints and reactive power output to maintain stability in dynamically-varying operating conditions. Connecting this model with numerous in bigger simulation environments will allow the control algorithms to be validated such as figure 3.2 a phasor model of a STATCOM in MATLAB Simulink is connected to all of the important components including voltage sources, reactive power controllers and signal scopes. Most importantly, it emphasizes the steady-state power flow characteristic and the interaction of STATCOM with grid components under normal operating conditions. This allows to illustrate and carry out the fluid modeling approach behind phasor models for system performance evaluation and control algorithm design giving computationally efficient simulation of large-power grids.

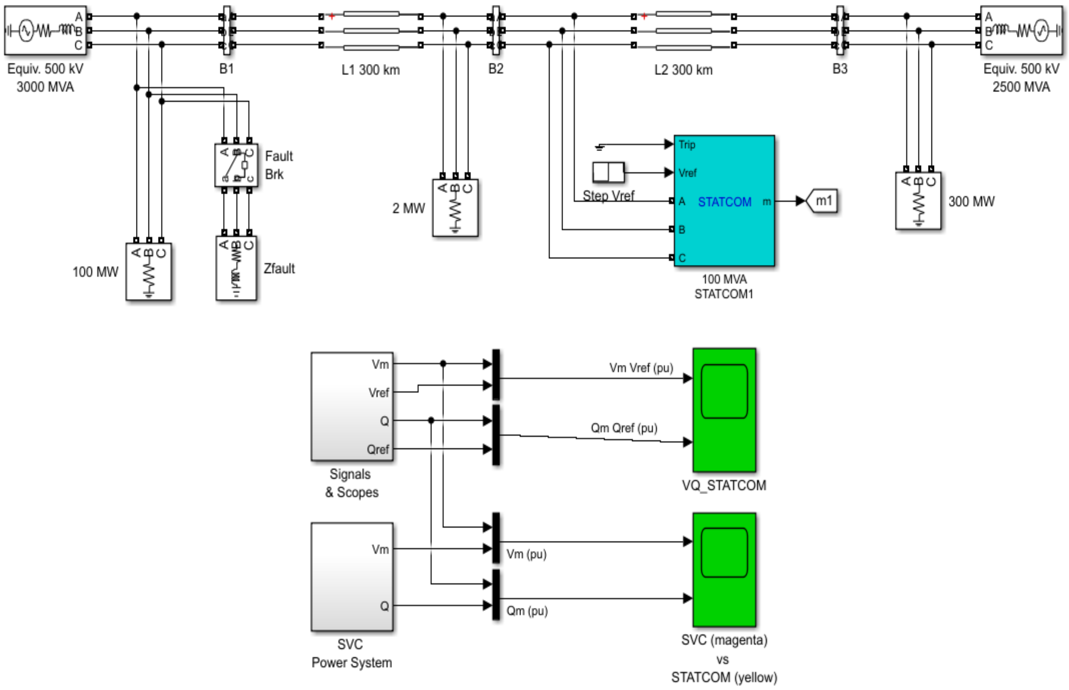


Figure 3.2. Phasor model of STATCOM [56]

Average model of D-STATCOM is a simplified form of the performance in the steady-state form discussing the capacity of the power electronic Components or switch or inverter as an induced or reactive absorptive power without analyzing the switching dynamics. This method eases computation time and yet does not limit the model to study voltage regulation and reactive power compensation without the need of high-frequency switching operation simulation. The average model is especially effective for system-level studies where the focus is evaluating the global effects of D-STATCOM on the power distribution grid instead of the internal operational characteristics guide. [57]

Figure 3.3: Average model of D-STATCOM connected to a 25 kV medium-voltage distribution network of system capacity 100 MVA A 3 MW/0.2 MVar reactive load downstream is connected after 21 km feeder (B1) and 2 km feeder (B2), which are represented by a programmable voltage source connected to the network. The placement of D-STATCOM is at Bus B3 for voltage regulation and to provide reactive power support to the system. It means that it can operate in terms of voltage stability within the normalized range (±3 MVar), so it can dynamically adjust both ends of a system according to system conditions, which implies balancing stable voltage at the PCC (point of common) connection.

A step-down transformer (25 kV/600 V) is integrated into the model to connect variable loads by using dynamic demand changes. The control system of the D-STATCOM commands the DC link voltage, allows for reactive power injection or absorption by modulating the indices. The system incorporates multiple monitoring points: Scope 1 is the per unit voltage and current at the PCC, which shows the performance of the D-STATCOM for voltage regulation. Scope 2 displays the active and reactive power flow on the B3 Bus and reflects the D-STATCOM's contribution to maintaining power quality. Scope 3 reflects the amount of reactive power exchanged by the D-STATCOM and displays its dynamic response to changes in load conditions. This configuration depicts the voltage regulation capability of the D-STATCOM in compensating for reactive power imbalance caused by changes in load. The average model shown in Figure 3.3 accurately captures the key operational characteristics of the D-STATCOM while simplifying the simulation; hence, it is an excellent tool for analyzing the impact caused by reactive power compensation devices in the grid for power distribution. Average models balance complexity with simulation speed, and therefore effectively capture the dynamic responses of STATCOMs to medium-term system changes such as load changes and voltage fluctuations.

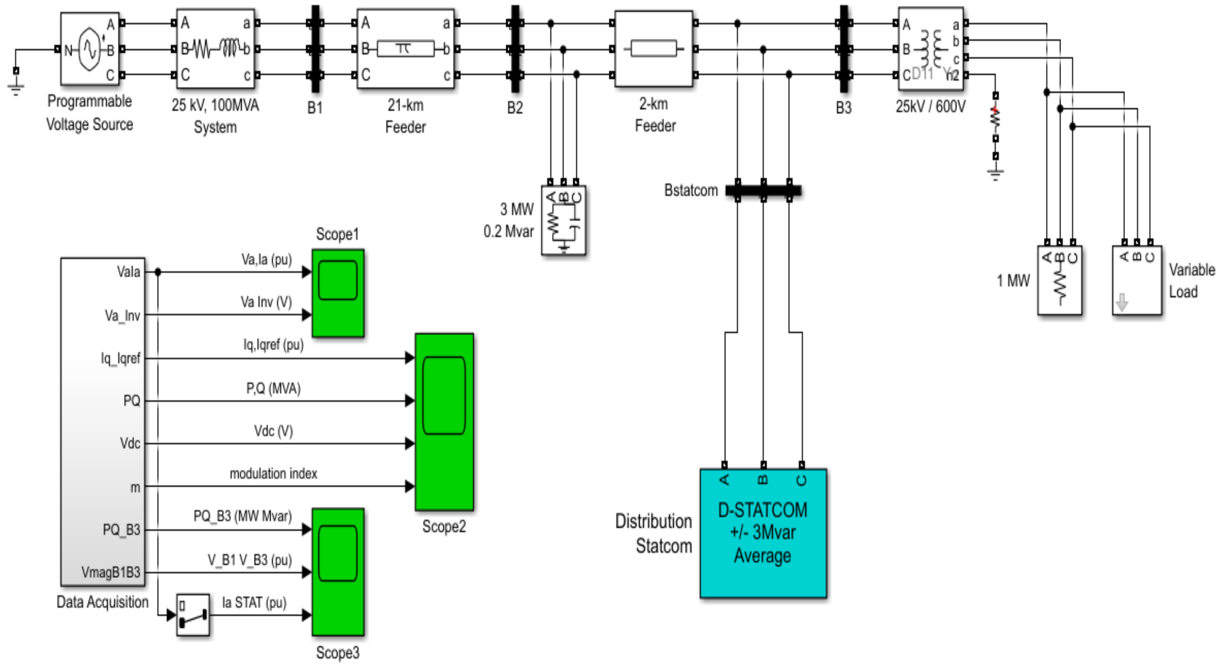


Figure 3.3 Average model of STATCOM [57]

In more complex analyses, detailed switching models simulate specific STATCOM switching actions to study high-frequency transients and harmonics.[58] Such models provide full performance verification of control algorithms, especially during rapid grid outages. Different STATCOM models provide insight into their effectiveness and guide the selection of appropriate strategies in different scenarios. The detailed model of STATCOM shown in Figure 3.4 provides an advanced representation of the operation of STATCOM in high voltage transmission network. This model is designed for a 500 kV system and includes critical elements such as interconnected transmission lines (L1: 200 km, L2: 75 km, L3: 180 km) with high-capacity networks equivalent to 8500 MVA, 6500 MVA and 9000 MVA. This product is rated for 100 MVA and connects B1 Bus. Its principal role is to maintain voltage stability and offer reactive power compensation.

The main STATCOM utilizes an advanced controller to regulate DC link voltage and E-connect pulses to control the VSC. It injects reactive power shown as "Q" at the PCC in accurate, stabilizing the voltage. The Cp and Cm of the STATCOM enhance the stability of the DC link voltage that affects the efficient operation of the STATCOM, and we need to mention Q26 here. These scopes are monitoring the three-phase voltage, the current, Q and the voltage for the current under variable conditions to help analyze the performance of the STATCOM.

The study uses a detailed model which provides a close insight into the dynamic performance, harmonic injection and transients of a STATCOM. [59] It also shows the STATCOM's operation in stabilizing the voltage profile through dynamic reactive power compensation, enhancing voltage quality, and minimizing losses in the network. This model is suitable for analyzing large-scale transmission networks because that also takes high-capacity transmission lines and equivalent networks into account, and it supplies complementary information to that of the average model, emphasizing transient and harmonic analysis.

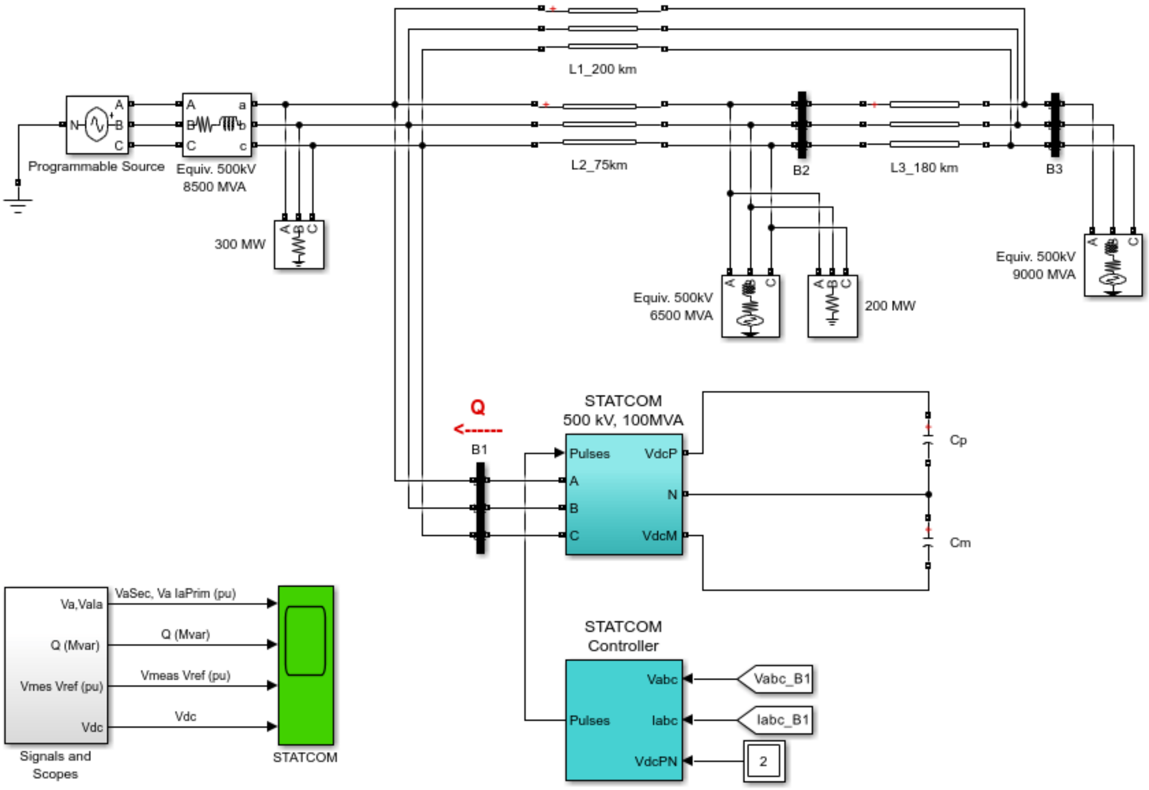


Figure 3.4 Detailed model of STATCOM [58]

In this regard, the simulation purpose is to implement adaptive control algorithms to QoS reactive power management in real-time. These algorithms will react in real-time to changes in the grid and to optimize not only steady-state performance but also transient behavior. This input is a real-time collection of grid data with voltage levels, adjusted reactive power demand and fluctuations of loads, all of which is fed to the aforementioned algorithms. For this, through real-time changes in STATCOM reactive power output, the algorithm dynamically considers voltage regulation by holding a voltage profile in the settled region. A company which provides that algorithmic answer to manage the variability of renewable energy is Solaris. This tilting is crucial for ensuring stability and minimizing the impact of renewable fluctuations on grid performance.

MATLAB Simulink Framework is designed and developed to analyze and simulate real-life cases contributing to the normal operating conditions of the Kurdamir City power grid. Among such disturbances are the voltage swingings with sudden load transients or line flaws, challenging the stability of STATCOMs to sustain the voltage level. Fast fluctuations of renewable energy sources, such as rapid decrease of solar generation as a result of passing clouds or demand peaks due to instant wind gusts are also modelled to test the algorithms for reactive power balance and voltage stability management capabilities. The model also considers dynamic load changes, such as peak loads on summer afternoons and winter evenings, that are examined to analyze the performance of adaptive control strategies under varying demand scenarios.

During the simulation study, the performance measures are voltage stability and the effectiveness of reactive power compensation. In Power Systems, Voltage stability refers to the ability of a power system to maintain steady acceptable voltage levels at all buses in the system after being subjected to a disturbance from a given initial operating condition. Also the effectiveness of a STATCOM compensation on reducing the unbalance in reactive power flow as well as in company with other compensation devices can be evaluated in terms of reactive power efficiency.

The results of the simulation are validated by comparison with benchmark data and experimental studies of similar systems. This guarantees that the results are applicable and relevant to the wide range of the grid worldwide that have similar characteristics. The significance of the results suggests that for the maintenance of the reactive power rand the grid stability under changing loads and renewable generation, it is essential to avoid the classical approach and go forward with adaptive algorithms.

MATLAB Simulink Simulations, In general, these show the performance of reactive power compensation methods under dynamic and difficult conditions. The incorporation of the advanced STATCOM models, adaptive control algorithms, and different test cases in the simulations validates the theoretical models and provides practical scenarios for their application. These two aspects characterize the degree of robustness and the level of effectiveness and efficiency of the electrical grid in Kurdamir City and this study aims to measure and analyze the role of adaptive algorithms in improving reactive power management and voltage stability.

3.3 Evaluation Metrics

A variety of assessment criteria are used to evaluate the performance of reactive power compensation solutions in this regard. Make sense of the solution performance, stability and energy efficiency with detailed solution performance insights that provide a deeper understanding of grid performance improvement. The combined use of metrics with adaptive methodologies enables the analysis of emerging strategies within a range of operational contexts, highlighting different facets of the electrical network and allowing a comprehensive overview of solutions obtained through different approaches.

Especially in grids that rely heavily on renewables, Voltage Stability is an important performance measure. In this criterion, how well the grid holds voltage levels in the presence of disturbance from load changes, fast changes in renewable energy production and faulty conditions or outages are examined. Simulation scenarios allow to monitor voltage profiles at critical nodes within the grid, comparing the achieved node voltage magnitudes to known limits, such as permissible deviation from nominal voltage level of ±5%, and evaluation of the performance of compensation devices, such as STATCOMs and capacitor banks that mitigate voltage sags or surge. Our proposed solutions facilitate the limitation of overvoltages or undervoltage to avoid damage to equipment but provide a stable level of voltages for the customers and ensure reliable power delivery to the consumers.

In addition to the above, Power Factor Improvement denotes the efficiency of handling grid reactive power requirements. This is a manifestation and reduces the load on generation and transmission systems by identifying the efficiency aspect of using electrical power. It measures the reduction in demand for reactive power and the level of power factor enhancement at specific load centers (critical load centers) at peak loading times owing to usage of compensation devices. The evaluation process includes calculating power factor values before and after the implementation of reactive power compensation, analyzing the ability of the proposed solutions to maintain power factors close to unity, such as 0.95 or higher, and measuring the reduction of penalties or inefficiencies associated with poor power factor conditions. The power factor improvement increases the operational efficiency of the grid and also reduces energy costs for utilities and end users.

Energy Efficiency is one of the main objectives of reactive power compensation strategies. This measurement reflects the amount of energy losses reduced by adaptive compensation. Network losses are mainly caused by high reactive power flow and voltage unbalance, which causes increased current flow and heating losses in transmission and distribution lines. The assessment focuses on total energy losses in the grid before and after the implementation of the proposed solutions, reductions in I^2R losses (thermal losses due to resistive heating in conductors), and measuring the overall effectiveness of the compensation devices in reducing unnecessary power consumption. This will not only increase the energy efficiency of the grid by reducing losses but also help achieve sustainability goals by reducing carbon emissions associated with power generation.

Grid Reliability refers to the degree to which a system operates continuously and provides power under dynamic and adverse conditions. This is one of the most relevant parameters, especially when integrating variable and intermittent renewable energy sources such as solar and wind. The assessment includes simulating sudden loss or reduction in output from renewable sources, such as rapid cloud cover over sunny spots or wind speed drops outside the wind farm operation area, analyzing the resilience of the grid to stable operation without significant disruption during such events, and analyzing the performance of an adaptive compensation strategy based on rapid changes in reactive power demand and uninterrupted power distribution. The increase in grid reliability ensures that consumers are less likely to experience outages and that the system can meet the challenges presented by the increasing share of renewable energy.

Transformer Loading is one of the key indicators to determine the operational stress and capacity utilization of transformers under different scenarios. An overloaded transformer causes increased losses, overheating, and reduced life, while underutilized transformers indicate inefficiency in the system design. The following should be evaluated: monitoring transformer loading at different times of the day, especially during peak demand conditions; simulating transformer behavior under reactive power compensation scenarios to assess stress reduction; and comparing loading levels before and after implementing compensation strategies to ensure optimum utilization. The suggested remedies keep the threat of overloading and failures at bay whilst couples load on the transformer to boost its effectivity and life.

Loss Minimization is an important aspect that needs to control the operation of the grid. This index quantifies both active and reactive power losses for maximum and minimum scenarios. Caution is exercised with regards to the active power losses (P), which are a consequence of current flow through the resistive components of the conductor resulting in resistive heating (I^2R losses) proportional to the square of current and volatilities. Subsequently, losses of reactive power (Q) are historically reviewed in relation to total inefficiency. It assesses the total system losses before and after the compensation, peak losses vs. low peak losses, patterns, and areas of improvement as well as how much losses were reduced by devices like STATCOMs and capacitor banks, etc. They can also help lower the operating costs for energy sellers while minimizing negative impact on the environment.

The criteria suggested for evaluation lay out a specific standard for determining the effectiveness of reactive power compensation solutions, with a focus on system stability and efficiency, in response to the issues arising from current energy consumption needs and renewable resource integration.

3.4 Limitations and Challenges

As much as this study offers a comprehensive perspective on the reactive power compensation strategy and its implementation within the context of the Kurdamir City grid, certain limitations and challenges must be acknowledged. Both modeling process and practical implementation challenges are interconnected, and demonstrate the difficulties in realizing and evolving modern power systems.

Simulating the dynamic structure of the Kurdamir grid is very challenging Kurdamir power network consists of diverse types of loads, renewable generation units and a seasonable demand profile. In modeling such a system, there is a trade-off between realism and computational feasibility. Modeling (linearization) of complex grid nodes, elimination of small grid elements is needed but this will affect the accuracy of functional simulation. As an illustration, some relations between distributed energy resources and the local components are barely a fraction of the whole complexity and might be missing in the analysis. Transient behavior, harmonic distortions, and equipment characteristic descriptions with high resolution (e.g., transformer saturation, time varying line impedance) require computational resources that may not always be available.

One training model can be used only for only one period. Your training model is relevant to a period of time, as well as your data. The models that you build will only work on data produced during this period. It should be taken into account that data is not available based on time. Without any, its hard to validate the simulation results against real performance. Although historical data is available, it may not capture the changes in the most recent load trends, resulting from current economic changes or increased renewable energy penetration. In addition, the lack of updated specifications for essential components such as transformers or capacitor banks lead to inaccuracies in simulations. Moreover, integrating data coming from different third-party sources (e.g., local utilities, renewable energy operators, government agencies) is a tedious task, as differences in their formats and standards introduce errors.

Implementation Feasibility: Most of the financial and operational challenges are serious in nature. Implementing simulation-based solutions into real-world applications involves massive investments in infrastructure upgrades, equipment, and cutting-edge technologies. The implementation of STATCOM devices or the installation of new banks of capacitors needs, in most cases, front-end, high costs out of the budget capacity of local grid operators, for example. _Furthermore, these projects need a significant amount of coordination and long-term planning to get them into alignment with grid operators, utilities and regulators. Resistance to change or inertia in the adoption of innovative solutions such as adaptive STATCOM systems can further slowdown their implementation. Additional adjustments may be needed to comply with local standards and regulatory frameworks, which could delay deployment timelines.

Renewable Energy Variability: Inherent uncertainties are introduced in both simulation and implementation. Solar and wind resources are intermittent by nature, and their generation pattern is difficult to predict. While modeled fluctuations are included in the study, real-world variability due to factors such as unexpected weather events or maintenance outages can deviate significantly. Ensuring consistent performance of reactive power compensation strategies under such fluctuating conditions remains a pressing challenge and thus limits simulations in replicating real-world scenarios.

Generalization of Results: The study is limited by certain characteristics of the Kurdamir grid. While the study focuses on this region, its findings may not be directly applicable to other grids with different configurations, load profiles, or levels of renewable energy integration. Adapting the proposed solutions to different regions will likely require modifications to address unique grid characteristics. Besides, scalability presents a problem in those effective solutions for the Kurdamir grid might be difficult to extrapolate to larger or more complex grids, where inter-regional power transfers and multi-stage voltage regulation are essential. Further complicating these processes are computational and technical challenges. Even with the availability of advanced tools like DIgSILENT PowerFactory and MATLAB Simulink, each of these tools has some limitations, such as the computational time required for large-scale models and user-defined customization needed to capture unique grid behaviors. Advanced simulation techniques, like co-simulation of electrical and control systems, require very specialized expertise, which may not be available.

CHAPTER FOUR

SIMULATION AND ANALYSES

4.1 Analysis of the Baseline Thermal Plant Model

This chapter contains results gotten from the various simulation models developed for this study. The major focus of this study analysis is to perform a critical evaluation of the adaptive techniques of reactive power compensation in a grid-connected renewable energy system. It gives a huge understanding of the dynamic framework of the system when working under different operating conditions where the simulated results were obtained through DIgSILENT PowerFactory as well as MATLAB Simulink.

This segment begins by generating basic simulation model data around a thermal power generation distribution model. This temporal model is applied to reactive power compensation using conventional reactors and acts only for perspectives of assumptions, limitations, and challenges stemmed from conventional methodologies. The chapter will continue with how to model advanced compensation technique like STATCOM and how to integrate it into an active grid, after which real-time comparisons and analysis will be made by comparing old and new values. Beyond this, analysis will include extensive observation, graphs, and figures to back-up findings and conclusions from the simulations.

Figure 4.1 presents in detail the thermal plant distribution network, the Hybridized Parameter grid integrated with morphometric parameters through DIgSILENT PowerFactory software. It forms the base case to be compared with the traditional reactive power compensation methods for the analysis of the system. The network configuration, equipment details, and operational parameters within the figure establish a comparative backdrop of the present system with advanced compensation techniques discussed later in this chapter. The major components of the system are listed below:

1. Thermal Generators: The thermal generators constitute the heart of the plant amidst a queue of sources. The whole costing strategy provides active energy to feed into the distribution grid so that it may work within a desired range. The figure includes pertinent parameters for the generators, rated power, operational voltage levels, and their reactive power range, which gives a clear view of the capacity and performance of the generators.
2. Transformer: Transformers primarily step up or step down the voltage levels of the distribution system to ensure that transmission and distribution of power can be effectively and efficiently done. Figure 1 includes some data on transformer capacity, impedance values, and turns ratios, thus giving a rapid overview of how transformers regulate voltage and minimize losses within the power distribution network.
3. Busbars: The busbars are the nodes of power flow that interconnect different elements of a power distribution network. At each busbar, voltage levels, load distribution, and reactive power flow are indicated to enable a clear understanding of the dynamic conditions under which power flows across the system.
4. Conventional Reactors: Conventional reactors have been connected to specific buses to allow for fixed reactive power injection for improving voltage stability through reactive power management. Their positioning in the network has been indicated with respect to the figure, and further, details for placement and operation such as connection type and capacity have been described within the figure.
5. System Layout Representation: DIgSILENT PowerFactory uses single-line diagrams to represent the components and their interconnections in the power system. Figure 4.1 illustrates how the software visualizes the layout of equipment, power flow, and operational data such as voltage profiles and load distributions.

There is no STATCOM in this model, which shows that most of the plant relies on a traditional technology that might also come with limitations to address dynamic conditions in the grid. In relation, such a simple model will serve as a base for possible improvements that modern compensation techniques could provide in the following sections of the chapter. Reactive power compensation has turned out to be important in ensuring stability and efficiency within power systems. Conventionally, this is obtained at thermal plants through reactors. In practice, reactors are appropriately configured and tuned so as to maintain voltage and reactive power flow within limits. It is the configuration parameters that essentially indicate the operational behavior of a reactor and how it interacts with the rest of the system. Traditional reactor-based compensation methods, however, are faced with significant challenges in the context of electrical grids within Azerbaijan. These include a lack of flexibility to respond to rapid fluctuations in load and increasing variability due to the greater penetration of renewable energy sources. Reactors are also less effective in mitigating harmonic distortion and dynamic voltage instability, which are becoming more problematic given modern grid demands. Given these limitations, advanced solutions such as STATCOMs are required. STATCOMs have a better dynamic response, improved harmonic mitigation, and an ability to adapt to the evolving grid requirements make them more apt for grid stability and efficiency in Azerbaijan.

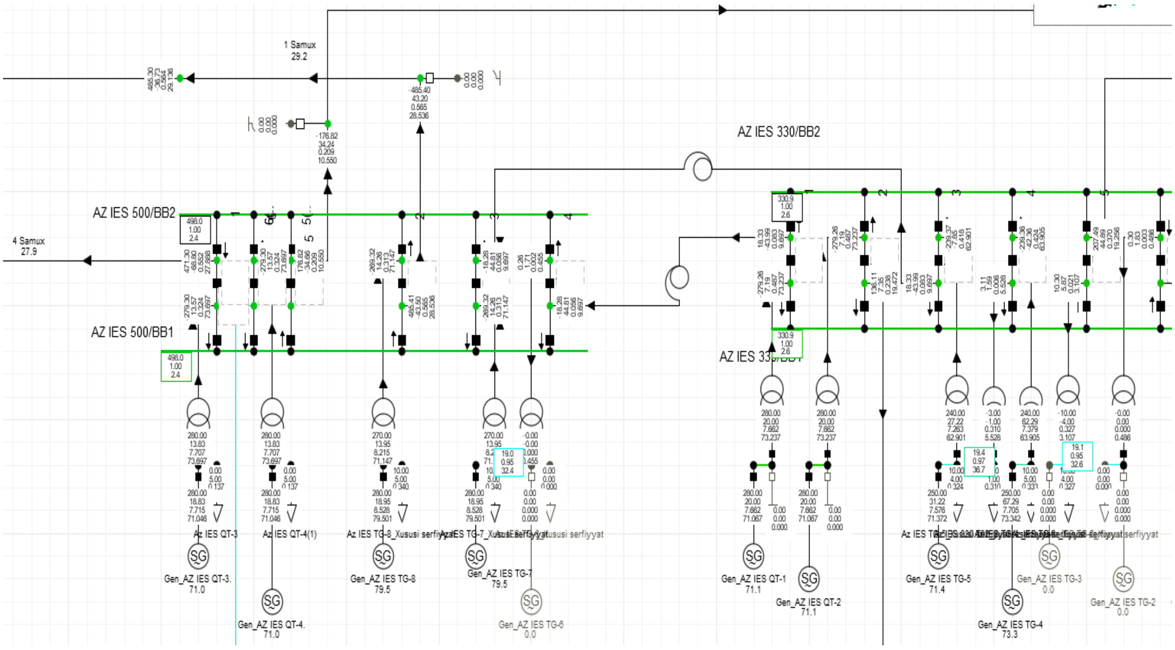
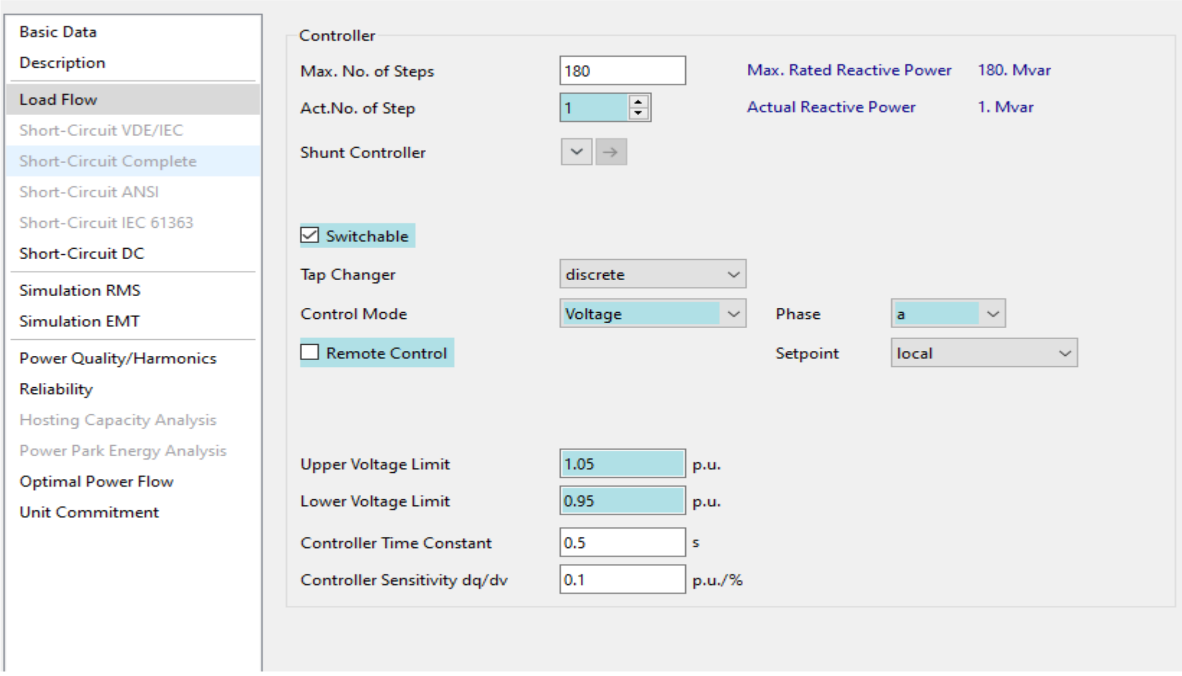


Figure 4.1. Baseline thermal plant model in DIgSILENT

Figure 4.2 shows how the reactive power compensation controller can be set in DIgSILENT PowerFactory to maintain voltage stability and efficiently manage the reactive power flow. The maximum value for reactive power that can be supplied by the controller is set to 180 MVAR, reflecting the reactive power supply or absorption potential of the device, depending on the system requirement. Under current conditions, the device injects 1 MVAR when operating at the first step of the total 180 discrete operating levels, thus allowing fine tuning of the reactive power output.

The controller is configured for voltage control mode while maintaining the system voltage between the lower and upper limits of 0.95 p.u. and 1.05 p.u., respectively, to prevent excessive grid voltage drops or increases under temporary changes due to variable loading conditions or interruptions. The sensitivity setting defines the gain at which the device will act to compensate for the reactive power due to voltage deviation; the time constant is set to 0.5 seconds to provide a fast response to the deviation. The “switchable” configuration confirms that the device can be dynamically activated/deactivated on demand, while the discrete tap changer mode provides graceful incremental control.

While classical reactive compensation approaches such as shunt reactors and fixed capacitors are quite efficient, their lack of dynamic response cannot cope with modern electrical grids. The large-scale integration of renewable generation sources into the power system creates a large amount of variability in power outputs, and static compensator devices cannot quickly adapt to rapid changes in grid conditions. Furthermore, classical reactors cannot cope with this complexity of voltage regulation in grids with highly penetrated distributed energy resources, creating inefficiency and stability problems. These are the restrictions which once again emphasizes the need of money compensation gear like STATCOM. Enabling rapid accuracy and adaptive reactive power control. Then, The next section shows how to model STATCOM to prove its practical advantage over traditional approach with the help of Simulink.



Controller

Max. No. of Steps: 180
Max. Rated Reactive Power: 180. Mvar
Act.No. of Step: 1
Actual Reactive Power: 1. Mvar
Shunt Controller

☑ Switchable

Tap Changer: discrete
Control Mode: Voltage
Phase: a
☐ Remote Control
Setpoint: local

Upper Voltage Limit: 1.05 p.u.
Lower Voltage Limit: 0.95 p.u.
Controller Time Constant: 0.5 s
Controller Sensitivity dq/dv: 0.1 p.u./%

Figure 4.2. Configuration of reactors in DIgSILENT

4.2 STATCOM Modeling in Simulink

Conventional compensation devices have become inadequate with the recent complexity of the modern electrical grids dynamic behavior in meeting both voltage regulation and reactive power management needs. Most existing compensating devices, such as fixed capacitors and reactors, are incapable of responding against rapid, high-frequency voltage changes due to a large penetration of renewable energy, distributed generation and time-varying load conditions. While STATCOMs or Static Synchronous Compensators only focused on dynamic injection or absorbers of reactive power. Due to its flexibility, accuracy, and ability to represent each component of the system in detail, Simulink is chosen as the simulation platform to analyze the results and understand the operation of a

STATCOM. Simulink is a sufficient platform for modeling all components in a STATCOM system because it supports VSC, DC link capacitors, transformers, AC filters and control system modeling. Unfortunately, the main STATCOM component in Simulink lacks such details. Data analysis in Excel, namely, optimization and the response of controlled variables to disturbances, is tedious, especially at the model level and provides limited information about component response. For STATCOM, Simulink acts as a good tool for examining its performance; with SIMULINK we can model control algorithms and examine how a system behaves in various grid conditions. A state space representation is used to accurately model and simulate the dynamic behavior of the STATCOM in MATLAB Simulink. This representation provides a mathematical framework for analyzing the interaction of the STATCOM with the power grid under varying operating conditions. The state space equations for the STATCOM dynamics are expressed as in equation 4.1.

$$\begin{bmatrix} \dot{V}_{dc} \\ \dot{I}_q \\ \dot{I}_d \end{bmatrix} = \begin{bmatrix} -\frac{1}{RC} & 0 & 0 \\ 0 & -\frac{R}{L} & -\omega \\ 0 & \omega & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} V_{dc} \\ I_q \\ I_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{C} \\ 0 \\ 0 \end{bmatrix} V_{grid} \qquad (4.1)$$

The state-space representation helps to simplify the analysis of STATCOM dynamics and modularizing the electrical parameters on which they depend.The initial equation defines the behavior of this manner DC-link voltage, it is rather vital that even when the grid is outside set stabel operational conditions be maintained.It is also possible to implement this in MATLAB Simulink where areas have been provided as blocks for STATCOM .

Figure. 4.3 Simulink Model of STATCOM: Many fundamental components are laid out and there roles in reactive power compensation. Also called as Voltage Source Converter-VSC, the essential part of the system is the two average models Bridge 1, and Bridge 2 converting DC voltage from DC Link to three-phase AC voltage.This VSC works in two modes: capacitive mode when it injects reactive power to raise voltage and inductive mode when it absorbs reactive power to lower voltage. The DC link is supposed to act as an energy reservoir that provides a constant supply of DC voltage to the VSC for proper performance.

The control system-D_statcom_avg-is the brain that ensures constant monitoring of various important parameters such as DC link voltage, reference voltage, grid voltage, and current.The inputs are then used by the controller to dynamically adjust the output of the VSC to maintain grid voltage within the predefined limits and ensure synchronization with the grid while maintaining efficient reactive power management. An AC filter is included to ensure high-quality power injection by removing high-frequency harmonics generated by the switching operations of the VSC. It also includes three single-phase transformers, Tr A, Tr B, and Tr C, for connecting the STATCOM to the grid. The transformers provide electrical isolation to step up or step down the voltage to match the grid requirements, hence allowing smooth reactive power injection

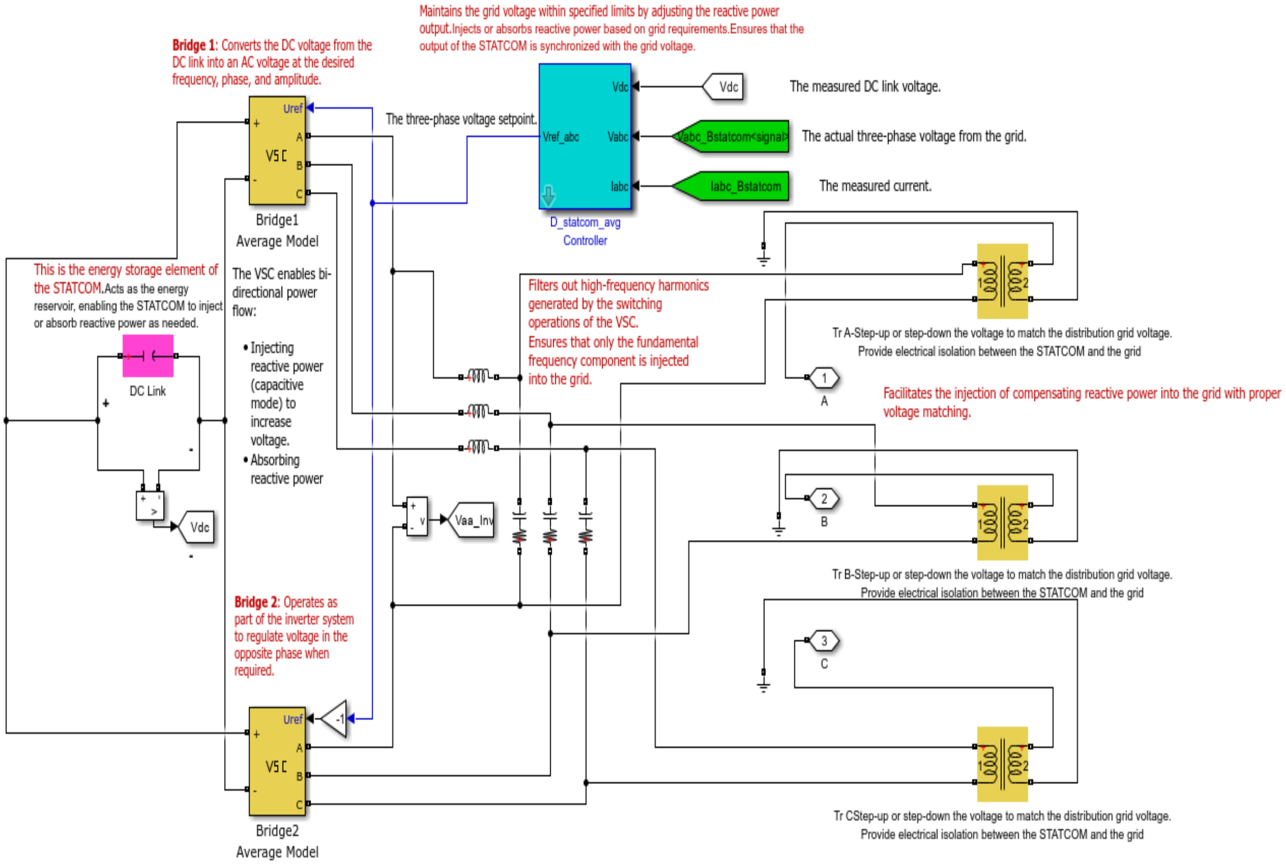


Figure 4.3. MATLAB modelling of STATCOM

STATCOM can dynamically exchange reactive power with the grid while regulating voltage dynamically, which is beneficial to the grid stabilization under different load and generation conditions. This is a simplified model using Simulink which models how the STATCOM behaves as a dynamic reactive power compensator and can respond fairly quickly to the demands in the grid. One provides an overview of how the different components of the STATCOM interact with each other, and highlights the key role of STATCOM in solving modern issues of electrical grid. Simulating such features in Simulink helps the model provide useful real time data in regard to the performance of STATCOM, thus experiencing its effectiveness towards integrating in complex power systems.

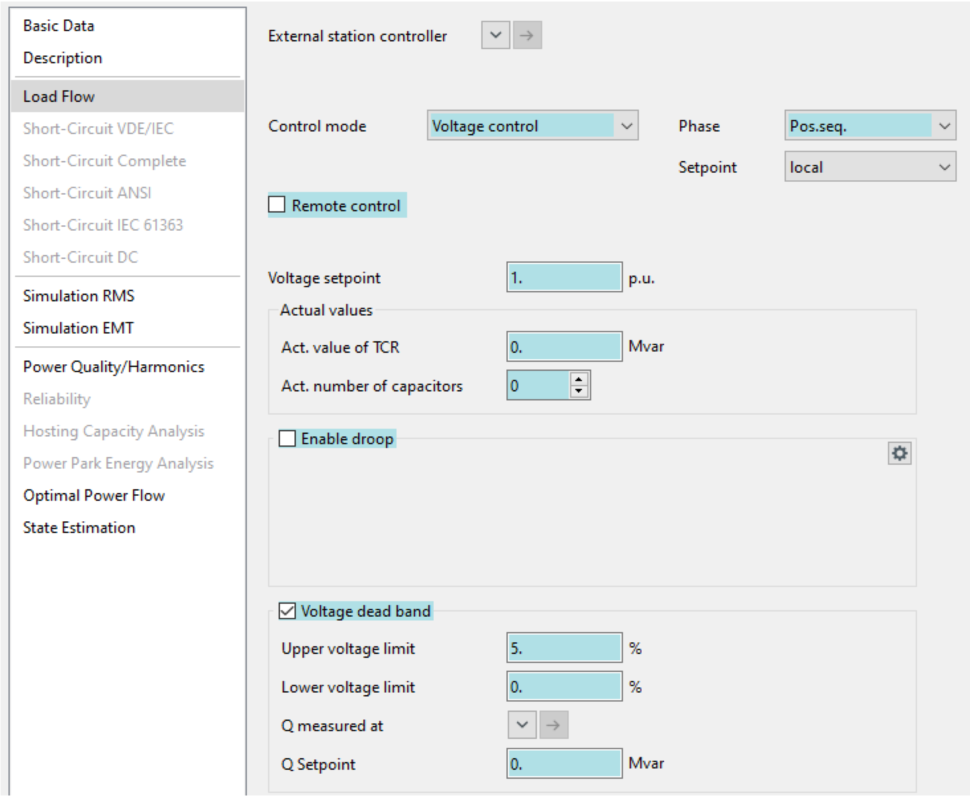
4.3 Development of STATCOM Model in DIgSILENT

SIMULINK-based modeling was rather a base for providing more detailed information concerning fundamental functioning principles of the STATCOM and great interactions between its components. So, each element such as VSC, DC link capacitor, control system, AC filter, transformers were examined in detail for its function and role in smooth operation of the STATCOM. Thus, the Simulink model as an early step to provide a glimpse into how each of the components would affect the overall performance of the system. We have learned, for instance, how the DC link stabilizes voltage, how VSC dynamically adjusts reactive power, and how the control system synchronizes with the needs of the grid. Also, the simulation hasntjust provided us valuable insights on how the system would react in different operating scenarios including disturbances like load variation and voltage sag.

With this knowledge in mind, we move to the next step, where, taking the detailed insight from the Simulink model, its application is done within the DIgSILENT PowerFactory environment. This involves the setup of the required parameters, system component configuration, and insertion of the values into the DIgSILENT dialogue boxes. The simulation in Simulink will provide a very accurate and optimized STATCOM model in DIgSILENT because the selections of parameters and the setting up of the system are informed by the result from the previous simulation. DIgSILENT enables us to conduct more advanced grid integration studies; we will thus be able to assess the STATCOM performance within real-world electrical network scenarios. In this regard, we use the exact values and configurations extracted from the Simulink simulation of the STATCOM model in DIgSILENT. It ensures that the model in DIgSILENT is robust, efficient, and represents practical operational conditions. This is one of the main steps needed for the validation of the capabilities of the STATCOM in modern power systems.

Figure 4.4 shows how a STATCOM is configured in a DIgSILENT PowerFactory environment; it lists the main parameters that will be needed for the STATCOM to provide effective reactive power compensation and voltage control. The STATCOM is thus configured to operate in voltage control mode, which ensures that the grid voltage is correctly regulated by dynamically injecting or absorbing reactive power. Control is based on positive sequence (Pos. seq.) of the voltage to ensure correct operation regardless of unstable system conditions. The STATCOM will be set to operate in local mode, i.e., it will act based on its own real-time measurements at the point of connection and without remote commands.

The Voltage setpoints defined as 1.0 p. u corresponding to the nominal voltage level. This becomes the target setpoint, with the STATCOM adjusting the reactive power output to maintain voltage stability. Voltage deadband is implemented with an upper limit of 5% (1.05 p.u.) and a lower limit of 0% (1.0 p.u.). During this range, no action is taken by the STATCOM, thus preventing unnecessary interventions on smaller voltage fluctuations and achieving operational efficiency. This deadband reduces wear and tear on the system by avoiding frequent switching and ensures smooth integration into the grid. Drop control is active, causing the STATCOM to react in proportion to voltage differences with its setpoint. It helps avoid over-correction at the point of installation and coordinates when there are multiple Reactive Power sources. In this case, the real values of Thyristor Controlled Reactor (TCR) and capacitor banks are equal to zero, which indicates that the STATCOM fulfills reactive power requirements without assistance from other compensating devices. The STATCOM's capacity for volatile and effective reactive power compensation, and correspondingly voltage stability, is illustrated in this configuration under changing load and generation scenarios. This DIgSILENT installation will sensibly integrate information from earlier related work, involving Simulink based modeling, which will result in a practical application of STATCOM technology that is capable of operating firmly within present day power networks.



External station controller

Control mode: Voltage control
Phase: Pos.seq.
Setpoint: local

☐ Remote control

Voltage setpoint: 1. p.u.

Actual values
Act. value of TCR: 0. Mvar
Act. number of capacitors: 0

☐ Enable droop

☑ Voltage dead band
Upper voltage limit: 5. %
Lower voltage limit: 0. %
Q measured at
Q Setpoint: 0. Mvar

Figure 4.4. STATCOM configuration in DIgSILENT

4.3.1 Integration of STATCOM in the Kurdamir Substation

STATCOM's integration into the existing power system marks a great step toward upgrading grid performance, especially with respect to voltage stability and reactive power management. The employment of STATCOM enables the transition of the Kurdamir Substation from the conventional reactive power compensation technique to a more dynamic and flexible solution. This not only enhances the reliability of the system but minimizes losses and strengthens the plant's capacity for handling varied load conditions. Figure 4.5 illustrates the addition of STATCOM to the Kurdamir Substation, showcasing the modifications to the system configuration and the critical connections involved. The following key aspects are detailed in this figure: Figure 4.3.1 depicts the electrical network of the Kurdamir 110 kV substation, integrating an SVS system and giving operating parameters at every node and bus. It thus configures the network of how reactive power flow is flowing through various nodes and buses along with the voltage magnitude that will help explain the use of reactive power compensation devices, including a STATCOM, for the grid stability study.

Network Overview: This figure illustrates the configuration of the 110 kV Kurdamir substation with different busbars marked as 2, 3, 4, 5, and 6, associated connected elements, and STATCOM incorporated at Busbar 5. It illustrates critical operating parameters, which involve voltage magnitude in kV and p.u., reactive power (Q), and active power (P), corresponding to each busbar for understanding the network performance. The following observations can be derived from the figure.

1. Voltage Magnitudes: The voltage on the different busbars is maintained close to the nominal value, as shown in terms of per unit (p.u.). Bus 2 (Kurdamir 110/1 SS): 102.4 kV (0.93 p.u.). - Bus 3 (Kurdamir 110/2 SS): 102.4 kV (0.93 p.u.).

2. Reactive Power Flow: The integration of the STATCOM into Bus 5 will contribute much to voltage stability by injecting or absorbing reactive power when it is needed: On bus number 5, the STATCOM actively provides reactive power to support the grid in maintaining the voltage within acceptable limits. Reactive power flows from high demand areas like loads connected to Bus 4 onward to other nodes, indicating the gravity of reactive power compensation in balancing the grid.

3. STATCOM and Reactive Power Management: The Static Var System, or SVS, which acts as a STATCOM on Bus 5, performs active management of reactive power, (Q), for the grid. The SVS helps to reduce the voltage deviations and maintains stability even with fluctuating conditions in load or renewable energy contributions.

4. Power Loss and Distribution: The diagram includes important measurements of the power loss across the grid. An example would be: The feeder sections between Bus 4 and other adjacent nodes show an active and reactive power loss and can highlight areas that require optimization. The reactive power exchange between the busbars shows a coordinated flow managed by the SVS to minimize grid instability.

5. Substation Design: Kurdamir 110 kV substation operates with a mixture of transformers and compensation devices, providing efficient power distribution between busbars. Each bus is connected to specific loads or network extensions that require a specific reactive power strategy to maintain stability while meeting demand.

Role of SVS in the Network

SVS integrated into Bus 5 plays an important role in the entire network for dynamic response whenever reactive power demand varies. This will keep the voltage magnitude within the range of operation during peak demand or in the event of an outage. A comparison between the situation of STATCOM-enabled and not-enabled situations will be done in the following sections of this section.

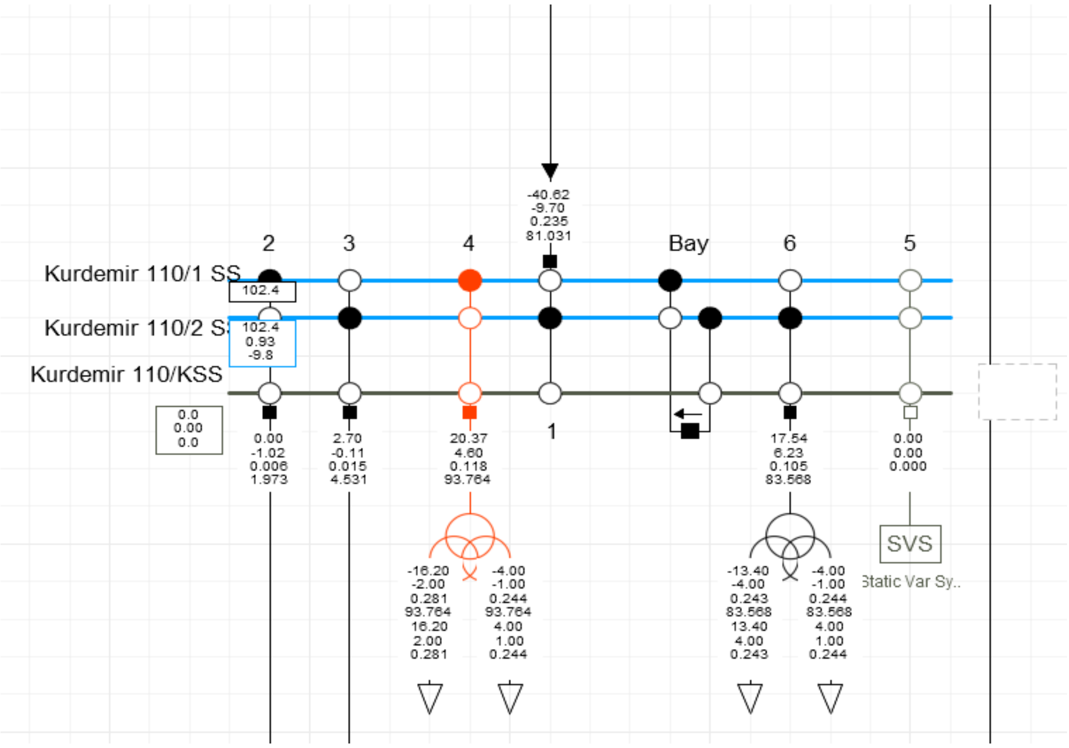


Figure 4.5. Adding STATCOM in Kurdamir substation

4.3.2 Voltage Regulation at the Main Bus of Kurdamir Substation

Voltage regulation is one of the most important aspects of the operation of a power system, since it affects stability, efficiency, and reliability directly. Voltage stability is one of the most important factors in maintaining the reliability and stability of power systems, especially in grids with high renewable and traditional energy penetration. There is a need for a generally accepted value to evaluate voltage stability. In this thesis, the developed L-Index is used, which measures the stability and reliability values at each bus in the power system. The L-Index is calculated as in equation 4.2.

$$L_i = 1 - \sum_{j=1}^{N} \frac{|V_j|}{|V_i|} * \left|Y_{ij}\right| * \cos(\theta_i - \theta_j) \qquad (4.2)$$

L_i-Voltage stability index for bus i.
V_j-Voltage magnitude at bus j.
V_i-Voltage magnitude at bus i.
Y_{ij}-Admittance of the line between buses i and j.
θ_i, θ_j-Voltage angles at buses i and j.
N-Number of buses connected to bus i.

By evaluating the L-Index values obtained from the system for all busbars in the system, weak areas requiring reactive power support can be detected and intervened to increase overall system stability and continuity.

$L_i = 0$ Indicates complete voltage stability at bus i.
$L_i = 1$ Represents voltage collapse at bus i.

The voltage levels at some key points of the system, such as the main bus of the Kurdamir Plant, show how well the compensation devices work and where improvements may be needed. Figures 4.6 and 4.7 present the comparative analysis of voltage ratings on the main bus at 4 PM under different conditions and provide a good insight into the system performance.

Figure 4.6 presents voltage magnitude and reactive power flow profile at Kurdamir 110 kV substation for peak demand at 4 PM. The diagram illustrates critical insight into the status of operation of the network: voltage magnitudes are in kilovolts (kV) and per unit (p.u.) values, with reactive power demands at important buses. The system voltage sags noticeably, and there are significant mismatches in reactive power without the active support of the Static Var System. This points to the challenge of maintaining stability in case of high demand conditions. Voltage levels at Bus 2 (Kurdamir 110/1 SS) and Bus 3 (Kurdamir 110/2 SS) are recorded at 102.4 kV (0.93 p.u.), which reflects minor deviations from the nominal voltage.

The stress on the system is further indicated by the reactive power flows in the network. High reactive power demand at key buses, like Bus 4 and Bus 6, contributes to voltage deviations, thus resulting in inefficiencies and potential power quality issues. During peak load conditions, such as those at 4 PM, the substation cannot maintain voltage levels within acceptable limits without an SVS or similar compensation device.

This figure gives an indication of the inability of the substation to handle peak demands without dynamic reactive power support. The voltage sag and reactive power imbalance observed call for the application of sophisticated compensation systems like STATCOM. These devices can dynamically inject or absorb reactive power to stabilize voltage levels, mitigate power quality issues, and enhance overall system reliability.

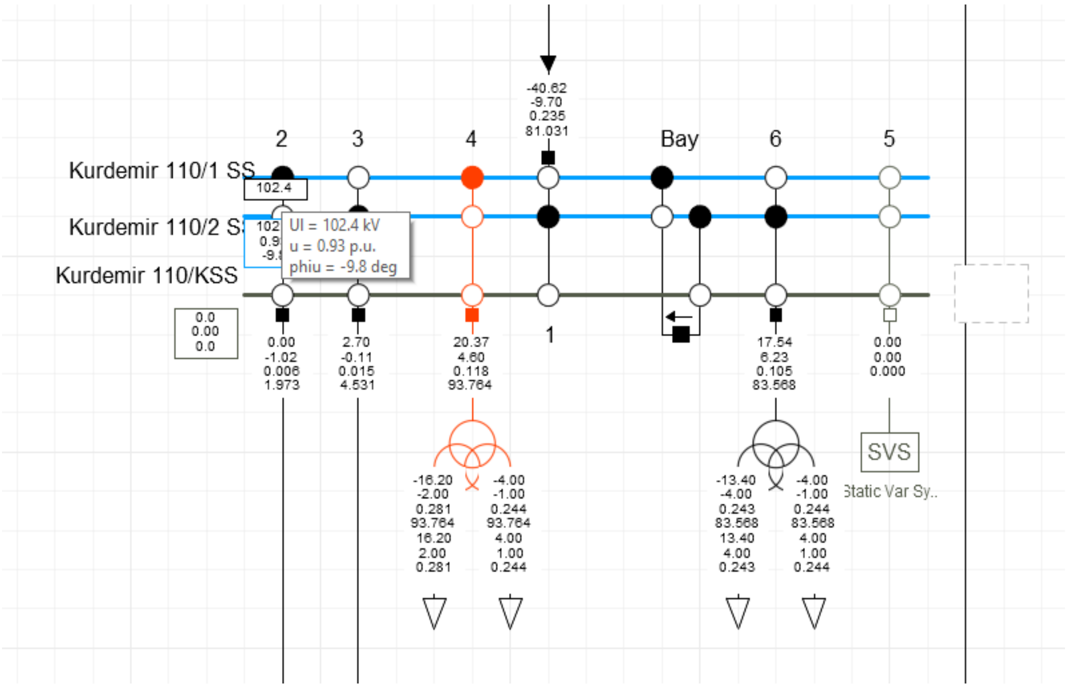

UI = 102.4 kV
u = 0.93 p.u.
phiu = -9.8 deg

Figure 4.6. Voltage values without STATCOM

On the contrary, Figure 4.7 presents the voltage ratings on the same main bus with STATCOM integrated. Here, the rated voltage UI reaches 110.0 kV with a per unit of 1.00. Such a result justifies an ideal voltage regulation case when the voltage value at the bus remains strictly at its nominal value. It is evident from Figure 4.7 that STATCOM can provide dynamic and accurate regulation of voltage under all operational ranges, even at maximum consumption.

The STATCOM dynamically controls the flow of reactive power by injecting or absorbing reactive power depending on the grid's requirement. At Bus 4, where the demand for reactive power is maximum at 20.36 MVAR, the STATCOM maintains voltage stability. This active compensation prevents further voltage drops and reduces the strain on the grid.

With its fast response and dynamic adjustment of reactive power, STATCOM is able to handle voltage deviations, especially under high demand conditions at 4:00 p.m. STATCOM stabilizes voltage levels, hence improving power quality, reducing losses, and enhancing grid reliability.

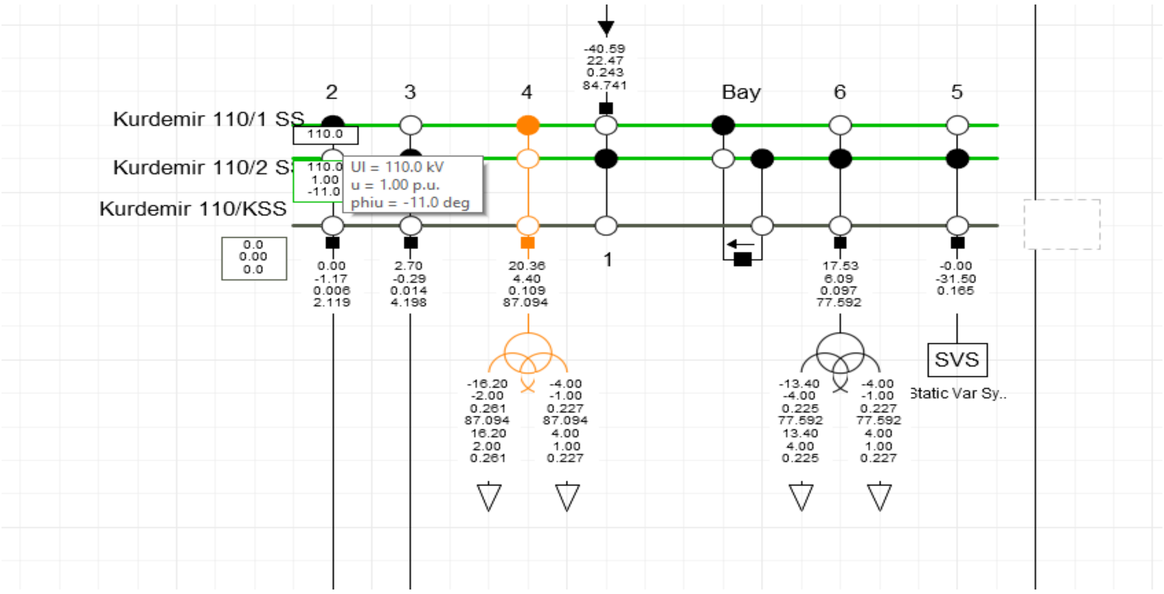
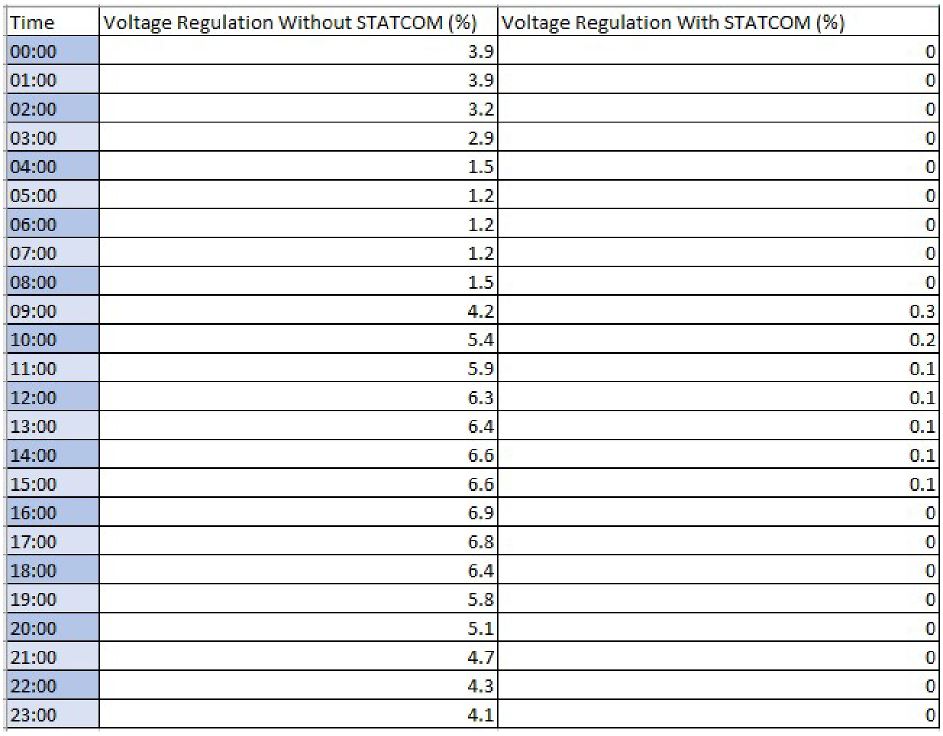


Figure 4.7. Voltage values with STATCOM

Table 4.1 presents a comparison of hourly voltage regulation based on both active and inactive STATCOM conditions. When comparing hourly data, significant conclusions are drawn for both scenarios. These data indicate a significant improvement in voltage stability during peak and off-peak hours with STATCOM implementation.



Time	Voltage Regulation Without STATCOM (%)	Voltage Regulation With STATCOM (%)
00:00	3.9	0
01:00	3.9	0
02:00	3.2	0
03:00	2.9	0
04:00	1.5	0
05:00	1.2	0
06:00	1.2	0
07:00	1.2	0
08:00	1.5	0
09:00	4.2	0.3
10:00	5.4	0.2
11:00	5.9	0.1
12:00	6.3	0.1
13:00	6.4	0.1
14:00	6.6	0.1
15:00	6.6	0.1
16:00	6.9	0
17:00	6.8	0
18:00	6.4	0
19:00	5.8	0
20:00	5.1	0
21:00	4.7	0
22:00	4.3	0
23:00	4.1	0

Table 4.1. Hourly voltage regulation of Kurdamir substation.

A comparison of Figures 4.6 and 4.7 clearly illustrates the impact of STATCOM on voltage regulation at the Kurdamir Substation main bus. This will definitely improve the system reliability, help in energy efficiency, and enhance overall grid stability. These will be discussed further in sections to come with regard to operational performance of the Substation. Voltage regulation is an important factor in stability and efficiency of power systems. It quantifies the degree of ability of the system to maintain consistent levels of voltage at different times of the day for assurance that the loads draw power at stable quantities without excessive fluctuations. Figure 4.8 presents the daily voltage regulation profile of the Kurdamir Substation, comparing scenarios with and without the integration of STATCOM. The blue curve of the graph shows the voltage regulation percentages without STATCOM throughout the day. As it can be seen, the system faces serious variations, especially during peak load periods between 9:00 AM and 6:00 PM. Voltage regulation values without STATCOM reach up to 6.9%, which shows large deviations from the nominal voltage that can deteriorate equipment performance and increase power losses. The voltage regulation values during early morning and late-night hours are relatively lower but remain above 1%, reflecting the inherent limitations of the system's traditional compensation methods in maintaining stable voltage levels.

In contrast, the orange curve represents voltage regulation percentages after STATCOM integration. The improvement is radical, with voltage regulation values maintained close to 0% throughout the day. This result reveals the dynamic reactive power compensation capability of STATCOM in order to damp voltage fluctuations, irrespective of changing load conditions. The STATCOM optimizes the operating conditions of the system and the connected loads, minimizing energy losses and improving overall system reliability. This analysis has shown how the STATCOM can completely change the face of voltage regulation at the Kurdamir Substation into a more stable and efficient power system that can respond to the demands of the modern era.

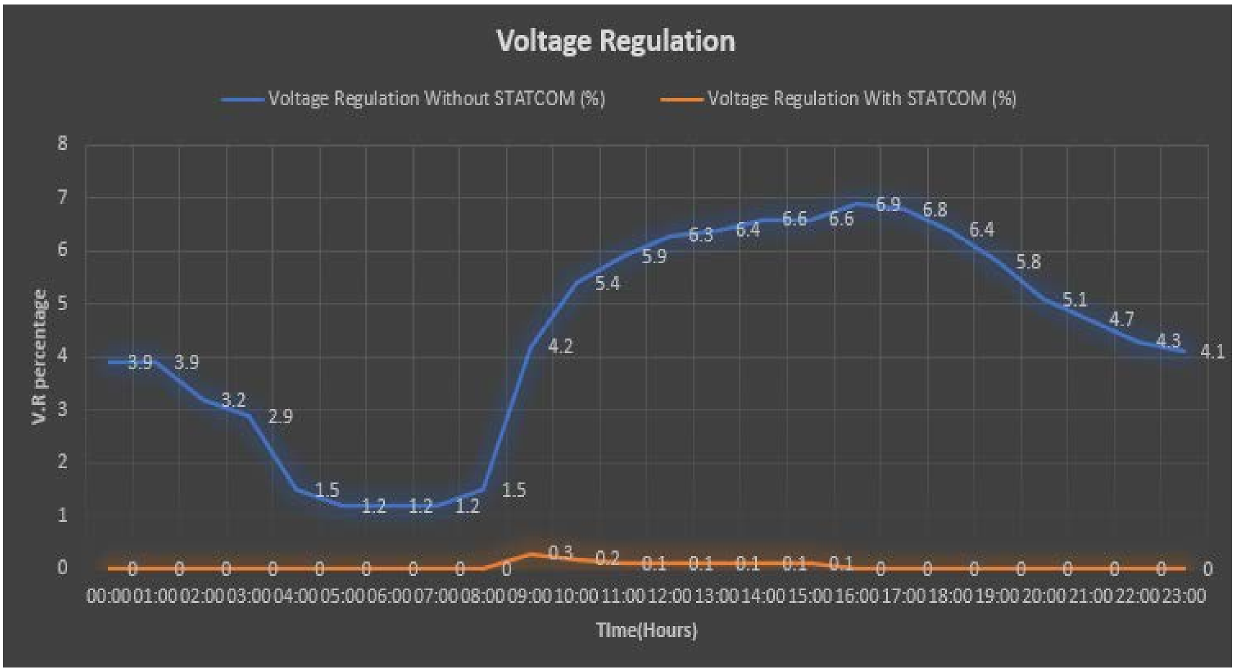


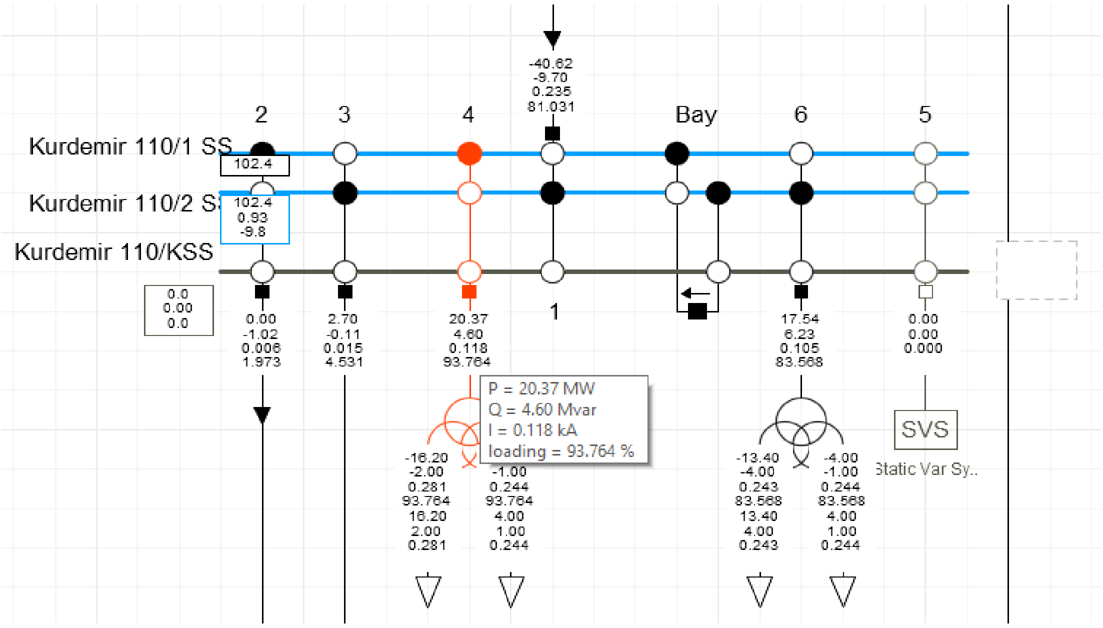
Figure 4.8. Analyses of hourly voltage regulation

4.3.3 Transformer Loading Analysis of Kurdamir Substation

Loading of the transformer is one of the crucial parameters in power system operations because it directly dictates the system's reliability, efficiency, and operational safety. To prevent overheating, reduce energy losses, and lengthen the lifespan, maintaining the loading within an optimum range is important. Below, comparative analysis of transformer loadings of the Kurdamir Substation for two situations is shown: without STATCOM and with STATCOM integration in Figures 4.9 and 4.10, respectively.

In the case of without STATCOM, the transformer loading is 93.764% as shown in Figure 4.9 This high loading level indicates that the transformer is operating close to its maximum capacity, which increases the risk of overheating, reduces efficiency, and accelerates wear and tear. Such conditions could lead to frequent maintenance requirements and a reduced service life for the transformer.

The voltage at Bus 4 is recorded as 93.784 kV (0.93 p.u.), which is below the nominal voltage level. In this condition, an increase in current flow through the transformer occurs to meet the high-power demand, hence increasing the loading and thermal stresses on the transformer. Poor distribution of power and increased stress on grid components are possible due to the lack of reactive power support from the STATCOM. This high loading is not only felt on Bus 4 but also cumulatively on the overall grid due to the reactive power imbalance. The inability of the system to manage reactive power dynamically, while the neighboring busbars such as Bus 6 are less loaded, puts great pressure on the transformers in the substation. This leads to reduced efficiency, higher losses, and an increased risk of thermal stress, especially on heavily loaded busbars like Bus 4.



P = 20.37 MW
Q = 4.60 Mvar
I = 0.118 kA
loading = 93.764 %

Figure 4.9. Transformers loading values without STATCOM

The transformer loading with the integration of a STATCOM is shown in Figure 4.10 These results have brought down the magnitudes of the loading to as low as 87.094%. In such a case, the great deal of improvement reflects the potential capability of a STATCOM in dynamically controlling reactive power for mitigating the reactive power demand on the transformer and reducing the thermal stress when this load is relieved for a transformer operating within more sustainable bounds, improving efficiency and reliability. Its presence also provides stability to the voltage in Bus 4 and keeps it at 87.094 kV or 0.94 p.u. significantly improved from low voltage conditions without STATCOM, voltage deviations were there causing higher flow of current and increased loading on the transformer. Dynamic injection of reactive power by STATCOM cuts down the voltage drops and enhances overall efficiency of transformer and grid.

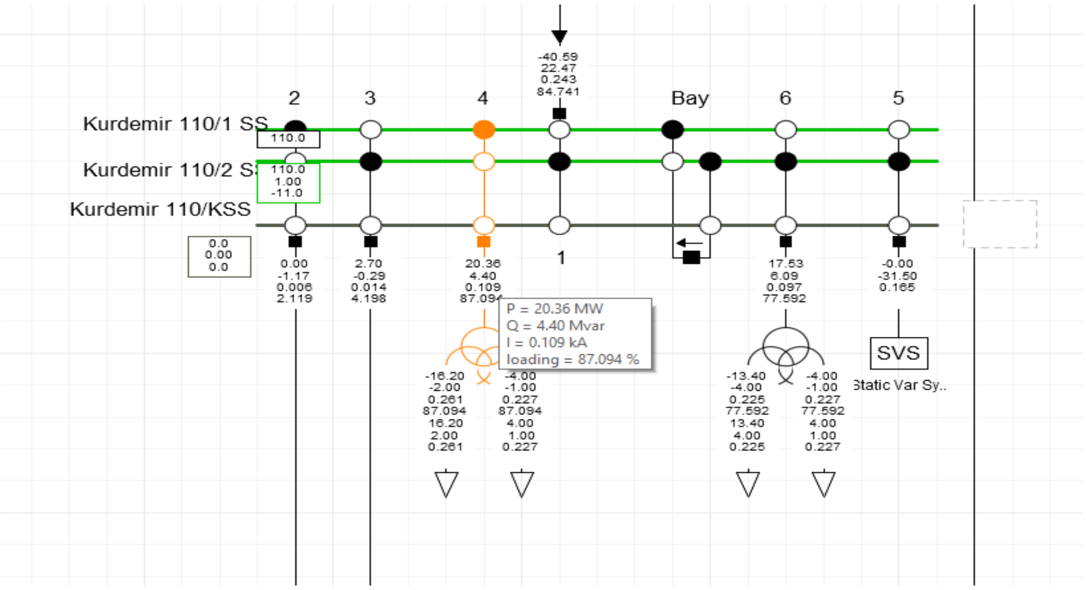
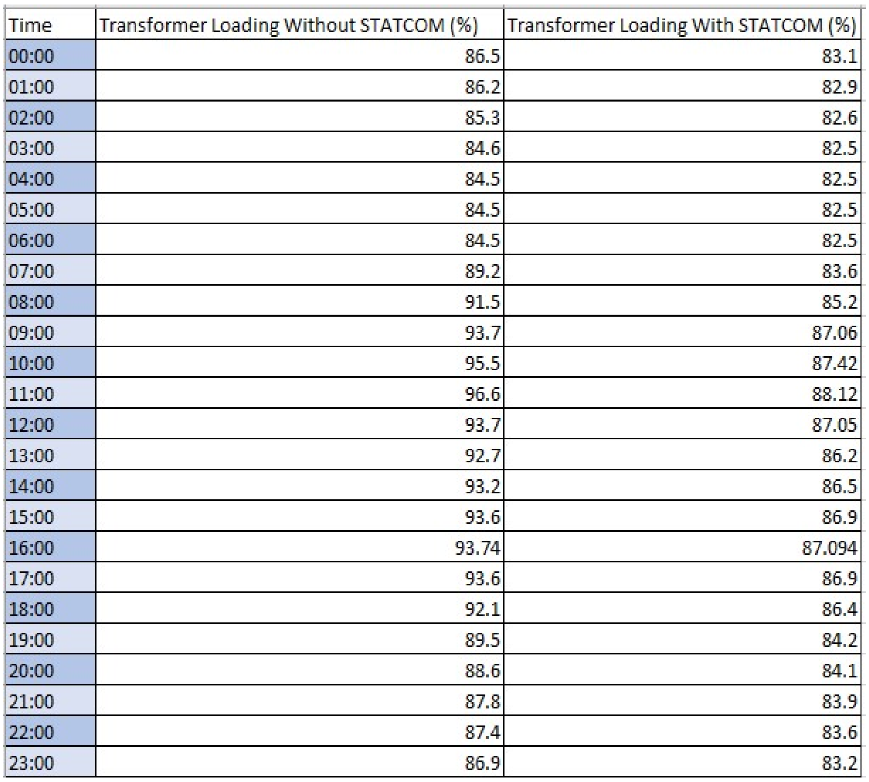


Figure 4.10. Transformers loading values with STATCOM

Table 4.2 presents the hourly transformer loading data for Kurdamir transformer center, comparing the two cases with and without STATCOM. The results show that there is a reduction in transformer loading with STATCOM integration compared to STATCOM-free, especially during peak load periods.



Time	Transformer Loading Without STATCOM (%)	Transformer Loading With STATCOM (%)
00:00	86.5	83.1
01:00	86.2	82.9
02:00	85.3	82.6
03:00	84.6	82.5
04:00	84.5	82.5
05:00	84.5	82.5
06:00	84.5	82.5
07:00	89.2	83.6
08:00	91.5	85.2
09:00	93.7	87.06
10:00	95.5	87.42
11:00	96.6	88.12
12:00	93.7	87.05
13:00	92.7	86.2
14:00	93.2	86.5
15:00	93.6	86.9
16:00	93.74	87.094
17:00	93.6	86.9
18:00	92.1	86.4
19:00	89.5	84.2
20:00	88.6	84.1
21:00	87.8	83.9
22:00	87.4	83.6
23:00	86.9	83.2

Table 4.2. Hourly transformer loading of Kurdamir substation.

Figure 4.11 illustrates the performance of STATCOM in mitigating the loading stress by comparing transformer loading percentages throughout the day at Kurdamir 110 kV transformer center. The blue line represents the transformer loading without STATCOM, while the orange line shows the loading when STATCOM is activated. This comparison shows the effectiveness of STATCOM in managing reactive power, stabilizing voltage, and relieving transformer stress. Without STATCOM, transformer loading rises to 96.6% at 11:00 AM, which is an indication of very near maximum capacity during high demand periods. Loading is consistently high throughout the day, particularly between 09:00 AM and 06:00 PM, reflecting the challenges of managing reactive power and voltage stability without dynamic compensation. This creates significant thermal and mechanical stress on the transformer, increasing energy losses and reducing operational efficiency. When STATCOM is activated, maximum transformer loading significantly reduces to 87.0% at 11:00, which is a huge improvement during peak demand hours. The dynamic injection and absorption of reactive power by STATCOM provide stable voltage levels and reduce the current flowing through the transformer. During low-density hours, such as late at night and early in the morning, transformer loading with STATCOM remains consistently low between 83% and 85% compared to the non-STATCOM scenario. The capability of STATCOM to reduce transformer loading by an average of 8-10% during peak demand enhances reliability and prolongs the life span of the transformer by limiting thermal stress. The more stable and smooth loading profile realized with STATCOM results in better load distribution and mitigates the risk of overloading and equipment failure.

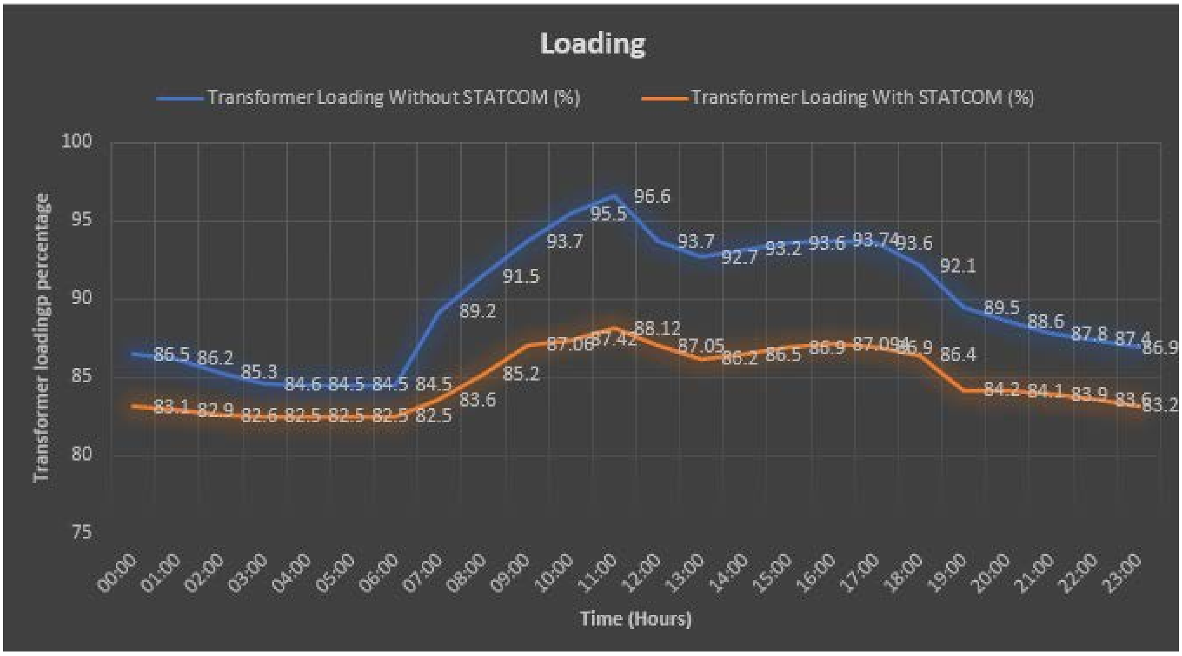
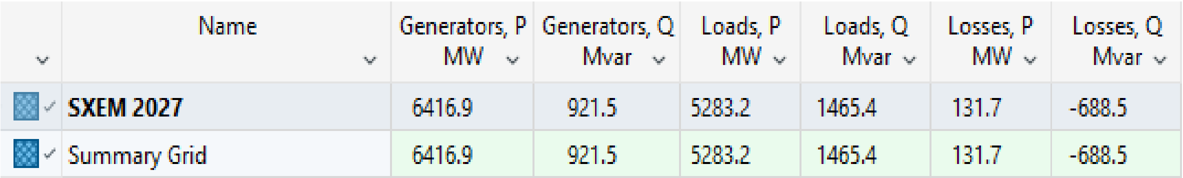


Figure 4.11. Analyses of hourly transformer loading

4.4 Power Loss Analysis with and without STATCOM

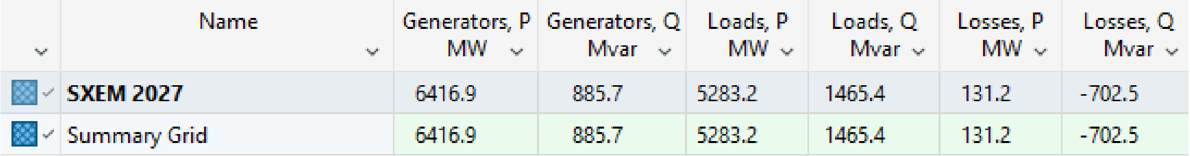
Loss reduction is one of the important aspects of power system optimization because losses are directly related to operational efficiency and energy cost.STATCOM, can contribute much to reducing active and reactive power losses. Tables 4.1 and 4.2 present a comparison of power losses at 4 PM in two scenarios: without STATCOM and with STATCOM.
In the case of without STATCOM as in Table 4.1 active power losses are P = 131.7 MW, and reactive power losses are Q = - 688.5 MVAR. These high values testify that reactive power demand affects badly on the overall efficiency, including large losses during transmission and distribution of power.



	Name	Generators, P MW	Generators, Q Mvar	Loads, P MW	Loads, Q Mvar	Losses, P MW	Losses, Q Mvar
▨ ✓	**SXEM 2027**	6416.9	921.5	5283.2	1465.4	131.7	-688.5
▨ ✓	Summary Grid	6416.9	921.5	5283.2	1465.4	131.7	-688.5

Table 4.3. Losses values at 4 pm without STATCOM

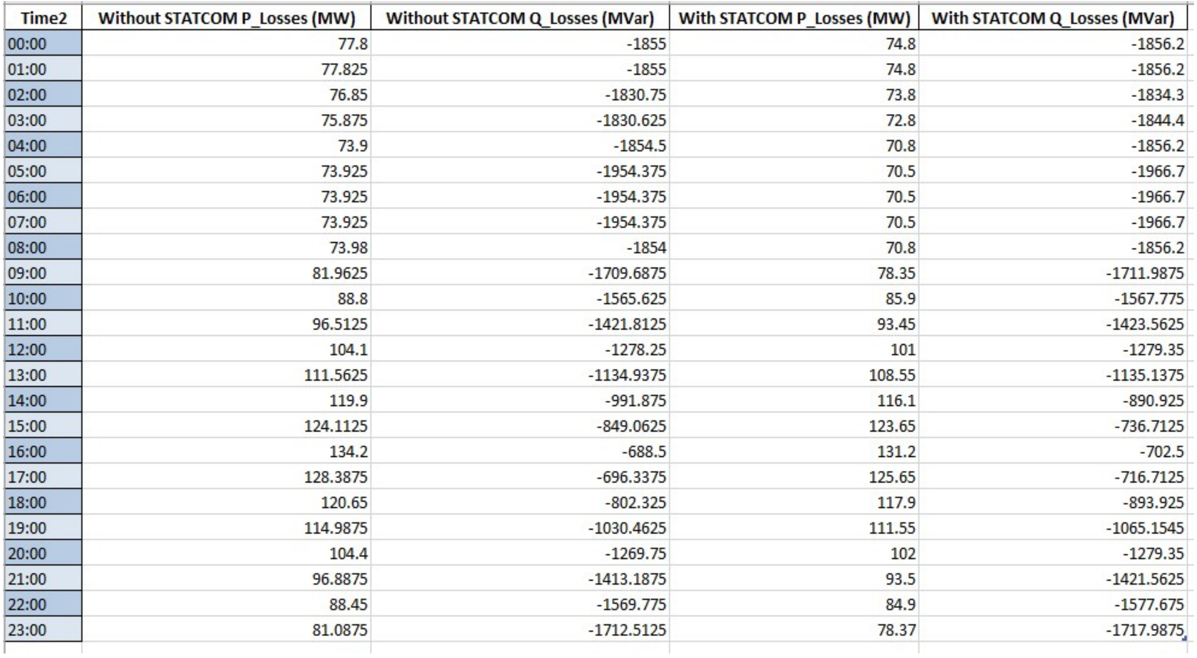
With the implementation of STATCOM, as depicted in Table 4.2, there is a reduction in active power losses to P = 131.2 MW, while the reactive power losses slightly increase to Q = -702.5 MVAR. The reduction in active power losses highlights the STATCOM's capability to stabilize voltage levels and regulate reactive power flow, thereby improving the system's overall efficiency. However, the increase in reactive power losses can be explained by the fact that STATCOM dynamically supplies the reactive power demanded by the system for better voltage regulation and stability.



	Name	Generators, P MW	Generators, Q Mvar	Loads, P MW	Loads, Q Mvar	Losses, P MW	Losses, Q Mvar
▨ ✓	**SXEM 2027**	6416.9	885.7	5283.2	1465.4	131.2	-702.5
▨ ✓	Summary Grid	6416.9	885.7	5283.2	1465.4	131.2	-702.5

Table 4.4. Losses values at 4 pm with STATCOM

Table 4.5 presents the results of the active and reactive losses in the hourly Kurdemir substation. It was observed that there was a significant decrease in losses, especially after STATCOM was included in the system. This analysis underlines the benefits of STATCOM integration in terms of improving active power efficiency while ensuring the system operates within stable voltage limits. The ability to manage and balance reactive power effectively outweighs the slight increase in reactive power losses, demonstrating STATCOM's vital role in enhancing the overall performance and reliability of modern power systems.



Time2	Without STATCOM P_Losses (MW)	Without STATCOM Q_Losses (MVar)	With STATCOM P_Losses (MW)	With STATCOM Q_Losses (MVar)
00:00	77.8	-1855	74.8	-1856.2
01:00	77.825	-1855	74.8	-1856.2
02:00	76.85	-1830.75	73.8	-1834.3
03:00	75.875	-1830.625	72.8	-1844.4
04:00	73.9	-1854.5	70.8	-1856.2
05:00	73.925	-1954.375	70.5	-1966.7
06:00	73.925	-1954.375	70.5	-1966.7
07:00	73.925	-1954.375	70.5	-1966.7
08:00	73.98	-1854	70.8	-1856.2
09:00	81.9625	-1709.6875	78.35	-1711.9875
10:00	88.8	-1565.625	85.9	-1567.775
11:00	96.5125	-1421.8125	93.45	-1423.5625
12:00	104.1	-1278.25	101	-1279.35
13:00	111.5625	-1134.9375	108.55	-1135.1375
14:00	119.9	-991.875	116.1	-890.925
15:00	124.1125	-849.0625	123.65	-736.7125
16:00	134.2	-688.5	131.2	-702.5
17:00	128.3875	-696.3375	125.65	-716.7125
18:00	120.65	-802.325	117.9	-893.925
19:00	114.9875	-1030.4625	111.55	-1065.1545
20:00	104.4	-1269.75	102	-1279.35
21:00	96.8875	-1413.1875	93.5	-1421.5625
22:00	88.45	-1569.775	84.9	-1577.675
23:00	81.0875	-1712.5125	78.37	-1717.9875

Table 4.5 Hourly active and reactive losses of Kurdamir substation

4.4.1 Daily Active Power Losses Analysis with and without STATCOM

The active power losses are one of the most important factors for estimation in the efficiency of power systems, as they relate directly to energy consumption and operating costs. The application of reactive power compensation systems such as STATCOM plays an important role in reducing such losses and enhancing overall grid performance. Figure 4.12 is comparing the daily active power losses at the Kurdamir Substation in two scenarios: one without STATCOM and the other with STATCOM.

Under loss conditions without STATCOM, active power losses continue to remain higher throughout the day, peaking to 131.2 MW at 4 PM. The significant magnitude of this loss quantifies how far the system is from maintaining efficiency under a heavy load condition and also identifies the insufficient reactive power compensation that is contributing to an increase in active power dissipation.

In contrast, the case with STATCOM presents considerable active power losses, whose peak value is 123.65 MW at the same time of the day. During the day, the STATCOM significantly reduces the power losses, especially during high-demand hours of the day, through effective voltage regulation and balancing of reactive power. This reduction not only saves energy but also reduces the thermal stress on system components, enhancing their longevity.

The general behavior of the Figure 4.12 reflects the performance of the STATCOM in mitigating the daily active power losses. In fact, any power system is burdened with losses, but it is at a minimum when STATCOM is interfaced, which helps the improvement of energy management and operation of the plant effectively. This comparison underlines reactive power compensation as a means to achieve sustainability and reliability in power system performance.

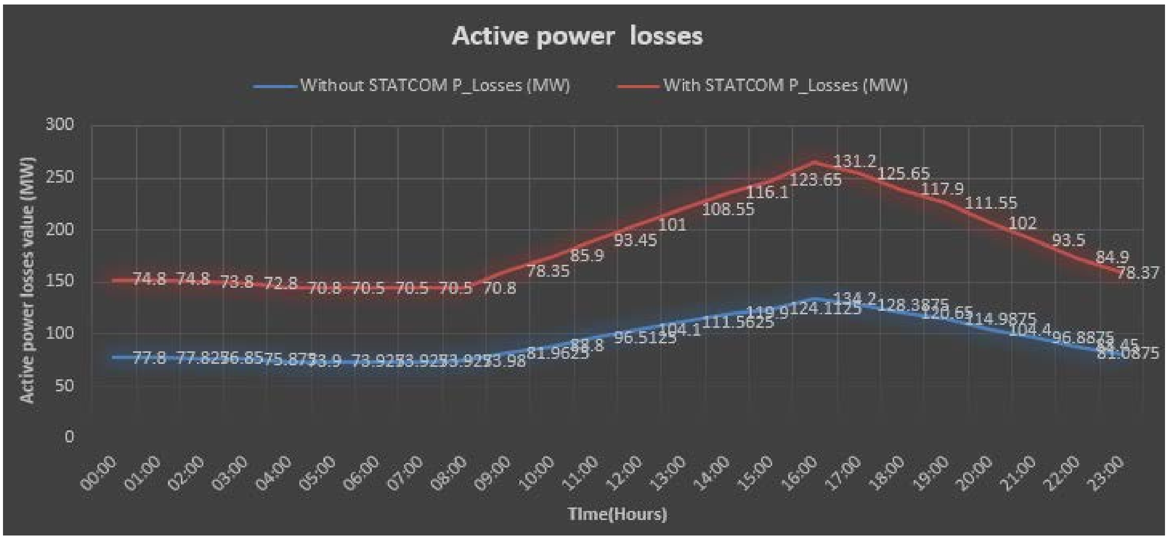


Figure 4.12. Analyses of hourly active power losses

4.4.2 Daily Reactive Power Losses Analysis with and without STATCOM

The losses due to reactive power (Q) are a critical factor that decides the efficiency and stability of power systems. The installation of STATCOM at the Kurdamir Substation aims at reducing such losses and increasing overall energy efficiency. Figure 4.13 shows a comparison of the daily Q losses for a day with and without STATCOM. In the case of without STATCOM, Q losses have higher values throughout the day. For example, at 12:00

PM, the losses peak at approximately -1709.6875 MVar. Similarly, during the early morning hours, around 1:00 AM, the losses are -1855 MVar, showing minimal variation at low-demand periods. It shows that the reactive power requirement and losses are higher in the system when STATCOM is not integrated. In contrast, the scenario with STATCOM shows a significant reduction in Q losses. The losses are considerably controlled, and the peak losses at 12:00 PM reach -1567.775 MVar, which shows a reduction of about 141.9125 MVar as compared to the case without STATCOM. During off-peak hours, the losses remain constant at -1856.2 MVar, the biggest improvement is during high-demand periods, where the reduction in losses directly correlates to improved voltage stability and system efficiency.

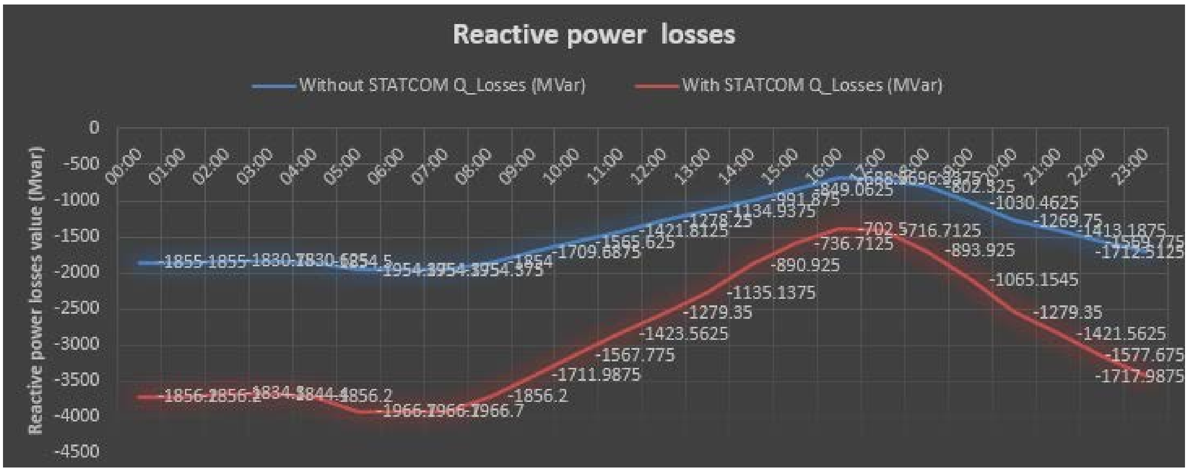


Figure 4.13. Analyses of hourly reactive power losses

Results

The installation of STATCOM at the Kurdamir power plant has proved that its operation can provide noticeable improvement in various operational parameters: voltage regulation, transformer loading, active (P) and reactive (Q) power losses, and system efficiency. These results put STATCOM in a very important position for enhancing power quality, system efficiency, and energy management.

Voltage Regulation

In the no-STATCOM case, the voltage regulation peak values extend up to 6.9% at the hour of 4 pm, which indicates a large change in the voltage magnitude during the day. But voltage regulation is minimized between nearly constant levels of around 0.0% and 0.4% for the case with STATCOM, and positive voltage magnitudes stabilize regardless of demand changes. The equipment recovery innovation drastically lowers the risk of asset damage and augments the reliability of the grid, elevating the process towards best in class performance of modern electrical systems.

Transformer Loading

STATCOM also has a significant impact when it comes to transformer loading. The transformer is operated almost fully loaded (93.764%) with the help of STATCOM. Over loading to this extent causes overheating, frequent maintenance needs, decreased longevity. However, the transformer loading can be brought down to 87.094% with STATCOM, thus giving us a considerable margin for safer and more efficient operation. Less loading means less stress on the transformer, extending its life and providing the same performance under different loading conditions

Active Power (P) Losses

To characterize the system efficiency for both the cases, the actual power losses were computed per day. In the absence of STATCOM, the system's active power losses are maximally 131.7 MW at approximately 4 PM, representing the energy loss during peak hours. With STATCOM at the same time, P losses reduce to 131.2 MW, in contrast. Though, this decrease seems insignificant at one timestamp, over a day, STATCOM's reduction accumulates to 1% P losses saving energy over a period of time.

Reactive Power (Q) Losses

The reactive power losses, crucial for maintaining voltage stability, are even more improved. In the case without STATCOM, Q losses are at their peak of -1709.6875 MVar at noon and higher throughout the day. In the case with STATCOM, Q losses reduce to -1567.775 MVar during peak periods, a reduction of approximately 141.9125 MVar. This consistent reduction in Q losses improves voltage stability, decreases reactive power demand from the grid, and enhances the overall efficiency of the power system.

Efficiency Improvements

The overall efficiency of the system can be evaluated by comparing the percentage reduction in both active and reactive power losses due to STATCOM. The efficiency improvement due to STATCOM can be expressed as:
These huge Q loss reductions reflect the effectiveness of the STATCOM to solve the reactive power challenges, while even the little reduction in P losses has accrued over time to energy savings.

Energy Management and Efficiency

The combined effect of reduced voltage fluctuations, decreased transformer loading, and minimized power losses underlines the great energy management benefits arising from STATCOM integration. By maintaining stable voltage levels and reducing active and reactive power losses, STATCOM will contribute to better energy efficiency, reduced operational costs, and improved grid stability. Such results show that STATCOM implementation is a sustainable and cost-effective solution for modern power systems facing variable loads and challenges of renewable energy integration.
Results The detailed analysis conducted here reveals that STATCOM radically changes the performance of the Kurdamir power plant in all respects. In a nutshell, STATCOM resolves critical problems related to voltage regulation, transformer loading, power losses, and efficiency; therefore, it enhances operational reliability and energy efficiency. These are the firm bases for the recommendation of STATCOM as part of modernization in power systems and grid stability enhancement.

CHAPTER FIVE

CONCLUSION AND FUTURE WORK

5.1 Key Finding

The research work is concerned with the design, testing and validation of new adaptive reactive power compensation methods applied in Kurdamir City power grid. From a general perspective, the idea of this work was to develop and test algorithms that respond in real time to changing load and renewable energy input for the most effective method of improving power quality and efficiency. Modeling and simulating various reactive power compensation techniques such as STATCOM systems, capacitor banks and distributed energy resources provided a rich understanding in developing the potential of adaptive compensation to improve grid stability under the widely permeating conditions of renewable energy integration. It also identifies the challenges and limitations in both the modeling process and practical implementation of such strategies that need to be addressed for successful real-world applications.

Effectiveness of Adaptive Reactive Power Compensation: The study confirmed the effectiveness of adaptive reactive power compensation algorithms in reducing power quality problems in Kurdamir grid. The algorithms showed a significant reduction in voltage fluctuations and an overall improvement in power system stability by dynamically adjusting the reactive power support according to real-time grid conditions. In particular, the integration of STATCOM devices proved to be a highly effective method to address reactive power imbalances, especially under variable load conditions and fluctuating renewable energy outputs.

Modeling Challenges: One of the main challenges was the inherent complexity of the Kurdamir grid, resulting from the combination of conventional loads and renewable energy sources, which made the demand profile highly dynamic. Simplifications made during the modeling process, such as linearizing some components or excluding small elements of the grid, reduced the accuracy of the simulations, especially with respect to interactions between distributed energy resources and local grid components. Furthermore, the lack of high-resolution data for transient behavior and harmonic distortions, and the difficulties in simulating equipment characteristics such as transformer saturation effects and changes in line impedance were highlighted, requiring advanced computational resources.

Data Availability and Validation: Real-time availability of operational data was another major limitation. While historical data provided insights into seasonal load variations and renewable energy output, the lack of live data from the grid made it difficult to validate simulation models against real-world grid performance. Additionally, integrating data from multiple sources, such as local utilities, renewable energy operators, and government agencies, presented challenges as formats and standards were not consistent. Despite these challenges, rigorous data validation processes, including cross-validation from multiple data sources, were used to ensure that real-world complexities in the Kurdamir grid were captured in the system model.

Financial and Institutional Barriers: The practical implementation of the proposed solutions faces significant financial and institutional barriers. Infrastructure upgrades, installation of STATCOM devices, and deployment of capacitor banks will require large investments that may be difficult to manage, especially in regions with limited budgets. Furthermore, the integration of high-value-added reactive power compensation technologies into the existing grid should be done in close coordination with local grid operators, utilities, and regulatory authorities; different levels of inertia or even resistance to change further slowdown the process. Compliance with local standards and regulatory frameworks may delay subsequent adjustments to the proposed solutions and their deployment.

Renewable Energy Variability: The large variability of sources such as wind and solar is a major setback in the design of reactive power compensation systems. The study modeled the fluctuation, but the actual variation may be quite different due to unpredictable weather conditions or maintenance shutdowns or such factors. Ensuring consistent performance of reactive power compensation strategies under such uncertainty is still a significant challenge and further research on real-time adaptive mechanisms is needed.

Scalability and Generalizability: Although the results presented in this paper are for the Kurdamir grid, the inferences obtained can be used to design an adaptive reactive power compensation strategy for other regions. However, the scalability of such solutions to larger and more complex grids is uncertain. Higher regional power

5.2 Conclusion

The study will present a holistic evaluation of the adaptive reactive power compensation strategies for the Kurdamir City power grid and give valuable insight into their potential to enhance grid stability and improve power quality. The results emphasize that integration of dynamic control algorithms with modern reactive power compensation technologies, like STATCOM devices and capacitor banks, will play a crucial role in overcoming the growing challenges brought about by the variability of renewable energy and complex conditions within the grid.

Nevertheless, many practical challenges have to be surmounted before these approaches could find their place in successful operation. These concern aspects such as limitations of modeling accuracy, availability of real-time data, financial, and institutional barriers, developing solutions that can tackle inherent uncertainty related to the weather. Despite these, this study gives very good ground for future research and development in adaptive reactive power compensation with great possibilities for practical applications in grids of different parts of the world.

The findings of the study further add to the contribution towards continuous development and research on how to come up with sustainable and efficient power systems that are able to integrate renewable energy sources while maintaining stability and reliability within the grid. In fact, by continuously improving and adapting the proposed strategies, it is possible to make electrical grids more resilient and able to meet future demands in the energy landscape.

5.3 Future Works

More research on adaptive reactive power balancing can be conducted in future enhancements to provide improvements in performance with the variance of grid conditions. And this could be one area, developing more powerful algorithms that work for higher load-of-renewable integration, and for grids with more complex layouts. Future work could also enlarge upon this study to explore hybrid systems which couples reactive power compensation with energy storage solutions, yielding functionally feasible options for real-world grid dynamism. The robustness of the proposed approaches could be enhanced if they are tested and validated not only on larger but also interconnected power systems or if the methods are examined at different renewable generation scenarios. Understanding how such solutions can affect grid hardware and associated operational and maintenance costs over the years will bring in valuable information for deployment at a larger scale.

The application of AI technology to reduce harmonics from advanced electronic systems, especially in systems using STATCOM and other advanced compensation methods, is certainly an exciting and compelling motivation for future exploration and development. AI-enabled control and optimization methods can significantly impact harmonic reduction and completely change the future of compensation technologies, which can naturally lead to improved power quality and system efficiency.

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