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Optimizing Power Grid Efficiency through Dynamic Reactive Power Compensation Using Capacitor Banks and Synchronous Condensers

Abstract: - As power grids transition to accommodate renewable energy sources like wind and solar, maintaining grid stability and efficiency has become increasingly challenging. A key issue is the management of reactive power (Q), which is crucial for voltage regulation and load balancing. Inefficient reactive power management can lead to energy losses, equipment strain, and grid instability. Traditional approaches often rely on advanced control systems, including Artificial Intelligence (AI) and Machine Learning (ML), but these are not always applicable in all regions. This study proposes a novel method to optimize power grid efficiency by using Dynamic Reactive Power Compensation (DRPC) through capacitor banks and SCs. Dynamic Capacitor Banks (DCBs), equipped with voltage-sensing equipment, will automatically adjust capacitance in response to real-time grid conditions, ensuring optimal reactive power supply. Synchronous Condensers (SCs) will stabilize voltage fluctuations, particularly in grids with high renewable energy penetration, by providing both reactive power and damping oscillations. The study will analyze existing grid infrastructure to identify areas of instability and high reactive power demand, using simulations to model the performance of these devices in improving voltage regulation and load balancing. Simulations conducted on a representative power grid revealed significant improvements in grid stability. Voltage deviation was reduced from ±10% without compensation to ±1% with SCs and ±3% with DCBs. Power Factor (PF) improved from 0.85 to 0.97, while reactive power losses decreased by 90%, from 10,000 kVAR to 1,000 kVAR annually. Furthermore, recovery times during faults were reduced from 8 seconds to 2 seconds with these methods. These findings demonstrate the potential of the proposed method to enhance voltage regulation, reduce energy losses, and stabilize grids transitioning to renewable energy. This approach offers a cost-effective, regionally adaptable solution, paving the way for sustainable and resilient power grids.

Keywords: Capacitor Banks, Power Grid Efficiency, Reactive Power Compensation, SCs, Voltage Regulation

1. INTRODUCTION

The global energy landscape is being rapidly changed as countries opt for renewable sources of energy such as wind, solar, and hydropower to curtail greenhouse emissions and the resultant climate change[1]. However, these alternative sources come with their fair share of difficulties in terms of intermittence and unpredictability that are impacting the stability and efficiency of modern power grids[2]. Traditionally, grids were designed to supply steady, centralized power[3]. Renewables introduce variability in the voltage levels and power quality and affect the overall reliability of the grid. This variability causes fluctuations and imbalances in voltages that may stress the grid infrastructure, especially when renewable energy penetration is high or when there are sudden changes in supply and demand. Reactive power is an indispensable constituent of electrical power systems and ensures that the voltage stabilizes and power is effectively transmitted[4]. Unlike active power which performs useful work, the reactive power supports the current to be transmitted by varying voltage levels and compensates for energy losses in lines of transmission[5]. Reactive power, thus, is crucially used to prevent voltage collapses, minimize energy losses and balance loads in grids efficiently. Even if the power grid has adequate active power, without

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enough reactive power, it may experience even more severe disturbances such as blackouts and equipment failure and reduced operations[6]. As such, maintaining reactive power is now crucial to grid stability, particularly with the increase in the integration of renewable energy sources[7].

Traditional reactive power management by fixed capacitor banks and older SCs often fails to have the flexibility and dynamic adaptability to address modern power grids[8]. Advanced control systems, AI, and ML have the potential to optimize reactive power compensation; however, the technology may not be feasible in regions with limited resources or technological infrastructure[9]. This creates a high demand for cost-effective solutions that can scale and are responsive in nature, and most importantly, adapt to real-time grid conditions without needing intricate infrastructure[10]. To fill in this gap, this work proposes a new reactive power management strategy that exploits the capabilities of DCBs and SCs, improving grid stability especially within high-integration renewable-based systems. There have been rising concerns with power grid stability and efficiency due to increasing dependency on renewable sources of energy. One of the key concerns is the unproductive consumption of reactive power, which ensures adequate voltage management and load balance[11]. Poor reactive power compensation may result in significant energy losses, equipment wear and tear, and higher instability in the grid, especially for systems with high variability in renewable sources of power supply. The solution of these inefficiencies is necessary for ensuring reliable and sustainable power delivery in modern grids[12].

The other approach that has gained quite much attention is DRPC. It helps in adjusting the supply and demand of reactive power in the grid and enables the maintenance of voltage stability with minimal losses in transmission and improved overall quality of power[13]. Capacitor banks and SCs are considered to be two of the most effective technologies for reactive power compensation[14]. Capacitor banks are less expensive and faster means of reactive power support, especially under peak load conditions[15]. SCs, on the other hand, are a more dynamic and robust solution to transient disturbances and system inertia support. The two technologies complement each other as a way of improving grid performance[16].

A systematic structure of the paper deals with the challenges and advancements in reactive power management for renewable energy-integrated grids. Section 2 provides a problem statement; detailing the cause of voltage instability and inefficient reactive power compensation in modern power systems. Section 3 gives research motivation, highlighting the ever-growing demand toward dynamic and scalable solutions that accurately consider the variability of renewable energy sources. Section 4 is the discussion of Related Works, discussing critical analysis of existing approaches, their limitations, and gaps in addressing the problem. Section 5 develops the System Model, elaborating on the mathematical formulations and components along with the methodologies proposed for the solution. Section 6 deals with the results and discussion, which are substantiated by the simulation and comparative analysis of the proposed approach. Finally, Section 7 concludes the study with a summary of the major findings and future research avenues in adaptive compensation systems as well as advanced integration with smart grid technologies. This comprehensive structure ensures clarity, logical progression, and a focus on practical and theoretical contributions.

1.1 Problem Statement

As the global landscape transforms by becoming much more dependent on renewable energies, power grids are under severe challenges with regard to stability and efficiency. Managing reactive power is one of the most sensitive areas needing attention since such a variation directly affects voltage regulation and load balancing within the grid. Voltage instability, losses in energy, equipment damages, and general inefficiency of the grid are associated with inadequate or inefficient management of reactive power. Although there are promising current approaches using advanced control systems, involving AI and ML, they cannot be universal, especially for areas where infrastructures are less developed and where renewable energy is to be integrated more significantly [17]. The traditional methods of reactive power compensation, which are based on static capacitor banks, are unable to respond dynamically to fluctuating grid conditions[18]. Furthermore, there are not enough effective solutions to stabilize voltage fluctuations, especially in those grids with high renewable energy penetration, where rapid and unpredictable power variations occur commonly[19].

This research seeks to address these challenges by introducing a dynamic approach to reactive power compensation using capacitor banks and SCs. These devices are provided with real-time monitoring and adjustment capabilities, thereby making it possible to optimize voltage regulation and improve the efficiency of the grid. There is still a lack of clarity on how DCBs and SCs can stabilize grids with high levels of renewable energy penetration with varying reactive power demands. This study focuses on finding instability points in existing infrastructures and assessing the performance of these devices, giving insight into their capabilities to enhance the efficiency and stability of the power grid.

1.2 Research Motivation

Importance of the Topic: Power grid efficiency is very crucial in meeting the ever-growing demand for electricity, especially with the increased penetration of renewable energy sources, which tend to cause unpredictable fluctuations in the power generation process. Reactive power compensation is critical to voltage regulation and energy loss reduction, both of which directly affect the operational stability and economic performance of the grid. This research is therefore crucial in addressing the current demand for effective voltage management of modern grids, particularly when transitioning to more sustainable energy systems. In this study, through an examination of DRPC using capacitor banks and SCs, the efficiency optimization of the power grid is accomplished. These tools help regulate voltage and improve grid performance, but their integration and optimal deployment remain underexplored.

Research Goal: The goal of this study is to propose and analyze a new system for DRPC using capacitor banks and SCs. Employing real-time sensing and adjustment capabilities, the proposed system will optimize reactive power supply, improve voltage regulation, and ultimately improve grid performance. SCs are to be added to provide further stabilization in the form of voltage-flattening effects as well as support grids with a high penetration of renewable energy. This study focuses on high-penetration power grids with renewable energy, which present the highest potential for voltage instability and reactive power problems. The developed solution places high importance on adaptability in relation to various grid infrastructures so that it can be used under any kind of geographic or technological scenario. Simulation-based analysis has been considered as part of this research work to understand its ability in real-time scalability and the possibility of practical implementation in reality.

***Research Contributions*:**

- The paper proposes an efficient strategy for reactive power compensation, DCBs and SCs. DCBs and SCs compensate for both voltage stability and PFs in a grid that heavily incorporates renewable energy.
- The research develops comprehensive mathematical models and detailed system parameters, such as voltage, impedance, reactance, and PF, to analyze and simulate the interplay of reactive power compensation, voltage stability, and load dynamics in renewable-integrated grids.
- The advanced application of thyristor-switched capacitors allows for reactive power compensation in real time to correct transient and steady-state voltage deviations. This results in dynamic compensation, which makes the grid robust under fluctuating demand and renewable energy generation conditions.
- The study suggests a method of strategic placement for capacitor banks, which is sensitive to voltages and minimizes power losses. Practical considerations in terms of thermal limits, space available, and advanced control strategies all ensure efficient and reliable operation.

Broader Implications: The results of this research would carry much potential for future power grids, with regard to improving the resilience and efficiency of grids during increasing demand and renewable integration. This research might influence policy decisions regarding energy infrastructure development, and further innovation into smart grid technology. For example, the findings may have long-term benefits for reducing the environmental impact of energy generation by optimizing the use of existing infrastructure and minimizing energy waste.

The paper is structured as follows: It begins with an Abstract summarizing the research on enhancing the power grid's efficiency through DRPC and capacitor banks and SCs. Section 1, which consists of an Introduction, introduces challenges in renewable energy integration and necessitates better reactive power management. Problem Statement deals with the issues of voltage instability and inefficiency in the grid, while the Research

Motivation deals with the relevance of grid optimization. Section 2, Related Works Review existing solutions and their limitations. Section 3, System Model Describes the grid setup and compensation methods, followed by Dynamic Compensation Components, which detail the roles of CBs and SCs. Section 4, Results and Discussion Present simulation outcomes and show better voltage stability with reduced energy losses. The paper ends with Section 5, Conclusion and Future Works, summarizing findings and suggesting improvements, and a list of References supporting the study.

2. RELATED WORKS

In this section, studies are reviewed as related to the integration of renewable energy sources into power grids, discussing the methods for enhancement in grid stability, in specific relation to voltage and reactive power. The synthesis of methodologies discussed, with common limitations encountered across studies.

Shin et al.[20] presented a new control method for ESS with the objective of leveling out the active power output from RES, such as photovoltaic and wind turbine generation. As RES penetration increases, maintaining power quality, such as minimizing voltage and frequency fluctuations, becomes challenging. To address this, the authors enhance the traditional ESS control methods usually based on low pass filters (LPF) with additional reactive power control. This enhanced approach reduces ESS capacity requirements to smoothen fluctuations and avoids phase delay issues, common in LPF-based approaches. Simulation results using PSCAD/EMTDC validate the efficiency of the proposed method, showing better voltage regulation and reduced fluctuation in RES output. However, the approach still had problems related to the integration of reactive power control in dynamic systems, which needs further tailoring.

Afrasiabi et al.[19] proposed a multi-agent day-ahead microgrid energy management framework that is aimed to minimize energy loss and operating costs for various agents including conventional distributed generators, wind turbines, photovoltaics, demands, battery storage systems, and microgrid aggregators. The deep learning-based approach is developed by combining convolutional neural networks and gated recurrent units to forecast market prices, wind generation, solar generation, and load demand. Each agent exploits its historical data to predict needed parameters and maintains information privacy utilizing the alternating direction method of multipliers for distributed optimization; an accelerated ADMM variant is further proposed based on over-relaxation. The method is tested on a realistic test system, and it can be observed that the forecasting method proposed here works better than the other methods, whereas the accelerated ADMM outperforms standard ADMM and analytical target cascading. However, in practical application, issues arise from the complexity of the implementation of accelerated ADMM and its sensitivity to the historical data accuracy of the framework.

Kofinas et al.[21] proposed a cooperative multi-agent system for energy management in stand-alone microgrids, based on distributed and collaborative reinforcement learning in continuous state-action spaces. The study aims to overcome the challenges of guaranteed electricity supply and improved reliability, considering uncertainties from renewable sources and stochastic demand. There exists power production units, microgrids, which consist of solar panels, fuel cells and diesel generators, power consumers such as electrolyzers desalination plants, and variable electrical loads as well as a power storage, for example, the Battery Bank. The method using Fuzzy Q-learning considers autonomous functioning from those agents representing microgrid sub-systems but sharing state variables through their coordination. Experimental results show the control of individual agents to certain components and the efficiency of the overall multi-agent system in ensuring the supply of electricity and improvement in system reliability. However, dependence on the accuracy of sharing of state variables and the complexity of fuzzy Q-learning implementation in various environments is one of the potential drawbacks.

Fan et al. [22] examine the methodology of synchronous condenser integration into a power system to enhance the system's stability, reactive power compensation, and voltage stability when renewable energy is integrated into such a system. It uses detailed modeling and simulation to analyze how the deployment of SCs boosts system inertia and dampens voltage fluctuations caused by renewable sources with intermittent generation. The methodology is tested using MATLAB/Simulink for different operational scenarios. The MATLAB/Simulink tool is employed in testing the methodology for diverse operating conditions. The emphasis results are dynamic response with improvements on voltage regulation. Its weakness, however, involves operational costs being higher; in terms of mechanical wear system loss, the response rate takes longer to occur in power electronics systems. A particular challenge also in its implementation is the optimal location and sizing of SCs in complex grids. This solution works well for weak grids, but this does not scale well in rapidly evolving grid demands. Generally, the research establishes a base for hybrid approaches but leaves room for cost-effective and energy-efficient alternatives.

Rastogi, Bhat, and Ahmad [23] explored a systematic method to determine the optimal placement of SCs for improving voltage stability in power networks. This methodology develops a multi-objective optimization model considering aspects of voltage stability, minimizing power loss, and cost-effectiveness. The authors utilize simulation tools, such as MATLAB, for power network scenario analysis under various load conditions. The study focuses on integration with sources of renewable energy and analyzes whether SCs provide effective reactive power compensation. However, limitations include high costs in capital and operations using SCs. The optimization of placement could be too complex for practical application to large-scale power grids, and it can't react in real time to drastic changes in loading. Further, the dependence of this model on stationary data limits its direct applicability to dynamic fast-changing grids. The paper concludes that although SCs present a high stability value, hybrid approaches combining advanced power electronics may offer better scalability and efficiency.

Mohamed and Sami [24] deal with a methodology to improve the reactive power injection by using SCs in hybrid power systems where renewable energy penetration is high. In this, the integration of SCs into the grid is modelled and its performance for different load and fault conditions is simulated. The study makes use of a case study approach employing tools such as MATLAB/Simulink to verify whether the condensers reduce voltage fluctuations and enhance the capability of fault ride-through. Indeed, the results reveal that the SCs help in enhancing grid reliability as well as reduce dependence on traditional generation sources for the provision of reactive power; however, the approach possesses certain limitations. These are high installation and maintenance costs, issues with mechanical wear, and also not scalable in modern rapidly evolving grids. The study further explains the challenge of optimal sizing and placement for maximum efficiency in large networks. It points out that though SCs offer robust stability support, they should only be used in conjunction with modern power electronic solutions if one is to get an economical and adaptable system.

Lee and Song [25] presented a methodology focused on the dynamic reactive power management of capacitor banks and SCs to improve voltage stability in the power grid. A simulation-based approach using MATLAB/Simulink for modeling various scenarios of power grids with differing reactive power demands and renewable energy integrations is proposed by the authors. Optimization algorithms are utilized to find the optimal configurations of reactive power compensators that minimize the cost and power losses. Despite being adequate to enhance stability and reduce dependency on fossil-fuel-based power generation, several limitations have been identified in the study. It has high implementation costs and is complex to manage hybrid grid systems, wherein real-time adaptability to sudden power fluctuations is limited. The approach is further restricted by its reliance on static optimization models, which do not fit well with very dynamic or decentralized grids. The paper concludes that combining traditional methods with advanced technologies, such as flexible AC transmission systems (FACTS), could overcome these challenges.

Most reviewed studies identified several limitations that exist when trying to deal with the challenges of renewable energy integration and grid stability. These commonly involve the integration of reactive power control into dynamic systems as well as complications in the use of more advanced optimization techniques sensitive to the accuracy of historical data. The use of the state variable requires accurate sharing, and applications of reinforcement learning techniques have been challenging in different environments. High operational and capital costs, besides the difficulties in optimal sizing and placement of SCs, are some of the significant drawbacks for dynamic and decentralized grids. Scaling issues, lack of flexibility to adapt to sudden power fluctuations, and dependency on static models are common problems. The recurring theme is that hybrid approaches, combining advanced power electronics and dynamic optimization techniques, can address these limitations effectively.

3. SYSTEM MODEL

The system model provides a mathematical and graphical representation of a power grid, capturing how it operates under varying conditions, such as changing loads and fluctuating voltage levels. This model serves as the foundation for simulating and analyzing the proposed reactive power compensation strategy.

3.1 Power Grid Representation

This research on power grid infrastructure is modern, transitioning towards renewable energy, but specifically on medium- to high-voltage systems where reactive power management becomes a critical factor in ensuring stability and efficiency. In a system involving the connection of power generation sources with the distribution system through high-voltage transmission lines, the presence of inductive reactance necessitates reactive power compensation to reduce voltage drops. The main renewable energy source under study, solar PV systems, utilizes power electronics that have a significant impact on the grid dynamics and reactive power balance. DCBs with voltage-sensing technology offer real-time capacitance adjustment to optimize the supply of reactive power, whereas SCs, being rotating machines, stabilize the voltage and damp oscillations in the grid, especially those with high penetration of renewable sources. Load centers, which include residential, commercial, and industrial loads, have different reactive power needs depending on their load profiles. Lastly, substations with transformers and circuit breakers manage the voltage levels and enable the flow of power from the transmission to the distribution networks. Figure 1 illustrates the power grid with the proposed reactive power compensation method, highlighting the integration of DCBs and SCs for improved voltage stability.

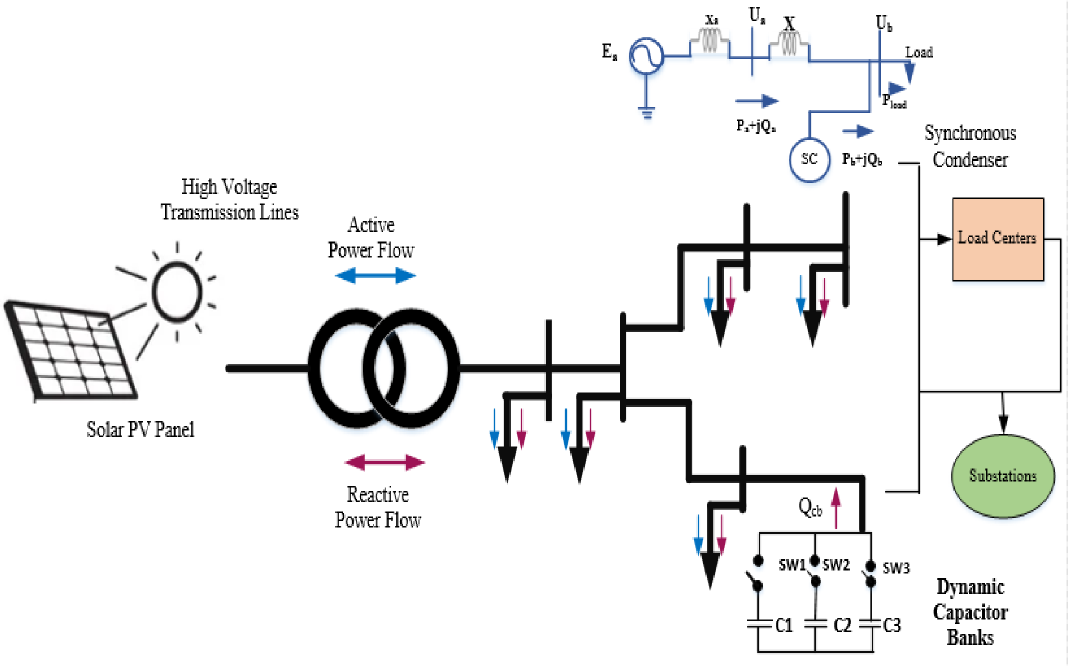

Figure 1: Power Grid Representation – Proposed Method

3.1.1 System Modeling and Parameters

The proposed methodology focuses on the integration of renewable energy sources into medium- to high-voltage power grids with an emphasis on reactive power management. The system simulation was conducted using specific circuit parameters, which are detailed in Table 1. These parameters represent the grid infrastructure, solar PV systems, compensation mechanisms, and load profiles essential for studying the dynamics of reactive power compensation and grid stability.

Table 1: System Circuit Parameters

Parameters	**Symbol**	**Value**
Solar PV System		
Number of PV converter modules per phase	n	4
PV Module Capacitor Voltage	V_{dcki} k=1,2,…n;t=a,b,c)	3000v (1.0 pu)
Capacitor size	C_{in}	1200μF(0.030 pu)
Switching frequency of power electronics	fsw	5 kHz
Filter Inductor for PV Inverter	L_f	4. mH (0.052 pu)
Grid Parameters		
Rated real power per phase	$P_{gt-rated\ (t=a,b,c)}$	1 MW(0.333 pu)
Rated reactive power per phase	$Q_{gt-rated\ (t=a,b,c)}$	1 MVAR (0.333 pu)
Rated RMS line-line voltage	V_{gL-L}	13.8 kV(1.0 pu)
Rated phase-ground voltage magnitude	$V_{gt}(t = a, b, c)$	8.0 kV (0.8 pu)
Compensation Systems		
Dynamic Capacitor Bank Capacitance	C_{dyn}	1500 μF(0.035 pu)
Synchronous Condenser Voltage Rating	V_{sync}	12.5 kV
Synchronous Condenser Inertia Constant	H_{sync}	4.0 s
Load Centres		
Residential Load PF	PF_{res}	0.92 lagging
Commercial Load PF	PF_{com}	0.95 lagging
Industrial Load PF	PF_{ind}	0.85 lagging
Substation Parameters		
Transformer Voltage Rating	V_{trans}	138 kV/13.8 kV
Transformer Reactance	X_{trans}	0.12 pu
Circuit Breaker Operating Time	t_{CB}	2 cycles (33.3 ms)

3.1.2 Mathematical Representation:

The grid is modelled using key electrical parameters such as voltage, current, impedance, power, and reactive power. The primary mathematical components include:

The real and reactive power flow in an AC power grid can be expressed using the following Eqn. (1) for each node i.

$$P_i = \sum_{j=1}^{N} V_i V_j \left(\frac{1}{X_{ij}} \sin(\theta_i - \theta_j)\right) \text{ for all i= 1, 2,…., N} \quad (1)$$

Where: P_i is the real power injected or consumed at node, $V_i and\ V_j$ are the voltage magnitudes at nodes are the$\theta_i\ and\ \theta_j$ voltage phase angles at nodes i and j, N is the total number of nodes in the grid.

The Reactive Power Equation is expressed in the Eqn. (2)

$$Q_i = \sum_{j=1}^{N} V_i V_j \left(\frac{1}{X_{ij}} \cos(\theta_i - \theta_j)\right) \text{ for all i= 1, 2,…., N} \quad (2)$$

Where, Q_i is the reactive power at node i.

The voltage regulation achieved through DCBs can be represented by the following Eqn. (3) and Eqn. (4), which adjusts the grid's voltage by providing reactive power compensation.

$$V_i(t) = V_{i0} - \frac{Q_{comp}(t)}{X_{dyn}} \tag{3}$$

$$\text{Where, } Q_{comp}(t) = \frac{V_i^2}{X_{dyn}} \,.\, \Delta\text{t} \tag{4}$$

In a system that integrates renewable energy, the total power balance should take into account the injection of real and reactive power from renewable sources, such as PV systems, and compensation mechanisms, including capacitor banks and SCs. Total active and reactive power in the system can be expressed as in Eqn. (5)

$$P_{total}(t) = \sum_{i=1}^{N} P_i(t) + P_{renewable}(t) - P_{loss}(t) \tag{5}$$

$P_{total}(t)$ is the total active power in the system at time, $P_i(t)$ is the active power injected or consumed at node, $P_{renewable}(t)$ is the active power generated by renewable energy sources (e.g., solar PV), $P_{loss}(t)$is the active power loss due to resistive elements in the transmission line.

The reactive power balance in the system is expressed as in Eqn. (6)

$$Q_{total}(t) = \sum_{i=1}^{N} Q_i(t) + Q_{comp}(t) + Q_{sync}(t) - Q_{loss}(t) \tag{6}$$

Where $Q_{comp}(t)$ and $Q_{sync}(t)$ represent the reactive power supplied by capacitor banks and SCs, and $Q_{loss}(t)$ is the reactive power loss in the system.

Transmission Line Impedance: Transmission lines in the model are represented by their impedances, given as: Z = R + jX, where R depicts line resistance, which shows ohmic losses, while X represents inductive effects. Residential, commercial, as well as industrial consumers have been considered while creating the load profiles for simulation in the grid. Residential loads typically exhibit time-varying profiles, peaking during evening hours; commercial loads are characterized by medium levels of demand but large reactive power due to the presence of HVAC; industrial loads have high-demand levels but low PF due to high inductive equipment content. The active power drawn from these loads is depicted as P+ j Q where P denotes the real power and Q the reactive power.

The nominal operating voltage of the grid is set at $V_{nominal}$=11 kV, with permissible variations of ±10%, ensuring voltage regulation criteria are met for residential, commercial, and industrial consumers.

Voltage deviations (ΔV): These are maintained within ±5% using reactive power compensation, with ΔV expressed in Eqn. (7)

$$\Delta\text{V} = \frac{|V_{actual} - V_{nominal}|}{V_{nominal}} \times 100\% \tag{7}$$

Reactive Power Compensation (capacitor): The need for dynamic compensation arises from the interplay between reactive power (Q) and system voltage, which is critical for maintaining grid stability. Capacitor banks supply static reactive power, defined as in Eqn. (8)

$$Q_C = \frac{V^2}{X_c} \tag{8}$$

Where$X_c = \frac{1}{\omega C}$ is the capacitive reactance, effectively countering inductive loads. On the other hand, SCs provide dynamic support by adjusting reactive power output in real-time based on voltage feedback, enhancing the grid's capability to handle transient and steady-state conditions. This comprehensive grid model forms the basis for analyzing and optimizing DRPC strategies under realistic operating scenarios.

Synchronous Condenser: The reactive power supplied or absorbed by a synchronous condenser is given in Eqn. (9)

$$Q_{Supply} = \frac{V_{exc}^2}{X_s} \text{ and } \quad Q_{absorb} = \frac{V_{exc}^2}{X_s} \tag{9}$$

PF (pf): The PF pf is defined as in Eqn. (10)

$$\text{pf} = \cos\phi \frac{P}{\sqrt{P^2+Q^2}} \tag{10}$$

It plays a critical role in system efficiency. Typically, loads operate with a PF between 0.85 lagging and unity. Therefore, Q is reduced by reactive power compensation to minimize the apparent power (S) and the related line losses. Dynamic behavior in the grid is also taken into account by including time-varying load patterns and transient events such as fast line faults and sudden load additions. These latter events cause voltage dips or imbalances, which need to be stabilized by rapidly restoring the relevant reactive power.

3.2 Dynamic Compensation Components

Dynamic compensation components are most crucial in maintaining stability in grids and efficiency. It primarily involves capacitor banks and SCs for dynamic reactive power management within the system, each independently designed for unique functionalities and application strategies based on system requirements.

3.2.1 Placement of DCBs

Capacitor banks are an important element in the power grid to be used for reactive power compensation. They are modeled as shunt devices that inject reactive power into the system and thereby improve voltage stability and PF. The contribution of such devices is proportional to their size and, thus, usually implemented wherever significant voltage drops or reactive power imbalances are expected to be present.

From placement aspects, capacitor banks will be placed at the most suitable candidate buses based on sensitivity studies of voltage and the technique of power loss minimization. Voltage sensitivity will show places in the network that demand reactive power the most - particularly locations having areas where voltage is in either swinging fluctuations or below desirable norms. Power loss minimization minimizes power loss along transmission lines, thus running a smoother, better-functioning system. The placement strategy maximizes reactive power compensation in these areas to minimize voltage drops and reduces the line loss that has a positive impact on the grid's overall efficiency.

Practical restraints like space availability and the thermal limits of the capacitor equipment, besides theoretical placement, also play important roles. Capacitor banks create heat during operation and are usually installed in areas where proper cooling facilities are available as well as space for maintenance purposes. Additionally, there are equipment restraints, including respecting thermal limits, to avoid overheating or causing damage to devices. Capacitor banks that are incorporated into the grid must meet the set requirements of the operational and safety protocols to ensure smooth and safe operation.

Control strategies of capacitor banks depend on the application. In static applications, capacitor banks can be switched ON/OFF either manually or through some automated control schemes. The amount of reactive power offered by static capacitors is constant and fixed. These are beneficial in stable grid conditions where voltage regulation requirements are predictable and constant.

However, for dynamic applications, advanced control strategies are required. One such technique is the application of thyristor-switched capacitors, which are used for DRPC. TSCs make use of thyristors to switch capacitors in and out of the circuit in real time based on the system's requirements. This allows for quick response to changes in the grid so that voltage stability is maintained in the case of transient events or sudden changes in load conditions. In order to stabilize the grid along with minimizing fluctuations in voltage, it is essential that the capacitive reactive power injection be adjusted in a dynamic manner. Figure 2 shows the Thyristor Switched Capacitor is given below.

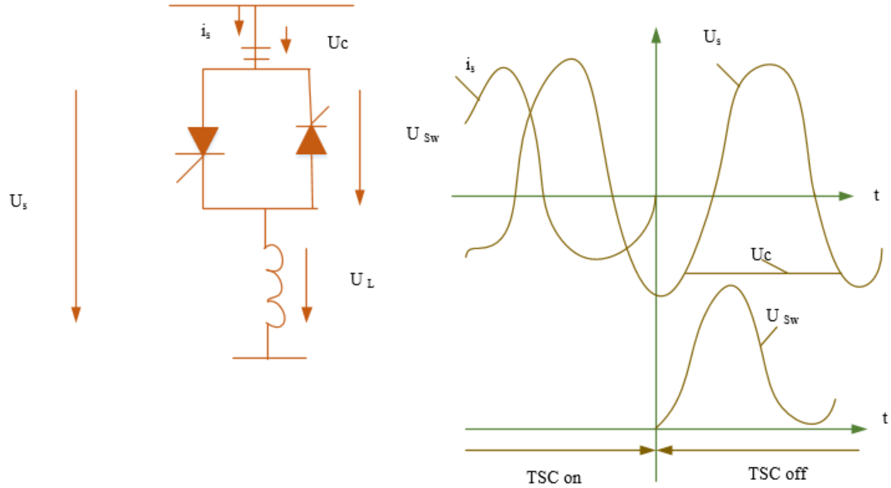

Figure 2: Thyristor Switched Capacitor

The integration of TSCs enables more effective and flexible operation of a grid, especially in systems with variable or fluctuating demand. In such situations, dynamic compensation is key because it accommodates rapidly changing loads and ensures a balanced grid. The speedy switching of capacitor banks on or off allows for real-time regulation of reactive power for improved grid resilience and better power delivery.

The strategic placement of capacitor banks in the power grid, depending on voltage sensitivity and analysis of power loss, would increase the efficiency of the power grid. Their static and dynamic control strategies enable the grid to respond effectively to changes in load and maintain voltage stability. Advanced dynamic controls, including the introduction of TSCs, improve further the flexibility and responsiveness of the grid system that is leading towards the development more stable and efficient ways to distribute power.

3.2.2 Functionality of SCs

SCs are electrically synchronous machines, working as generators or absorbers of reactive power according to the requirements of the grid. They do not produce real power but basically supply or absorb reactive power for improving the overall PF of the grid and sustaining the voltage stability level

The operation of a synchronous condenser is similar to that of a motor: a rotating machine may either absorb reactive power or deliver reactive power based on its excitation level. Excitation is the amount of DC current supplied to rotor winding. Depending on this current, the synchronous condenser may act as a source or sink of reactive power.

Reactive Power Supply: If the synchronous condenser is over-excited, that means field current exceeds the optimum value, it operates as a generator, supplying reactive power to the grid. It makes it easier in areas that experience a voltage drop; thus, it helps in strengthening the system voltage by injecting the reactive power. This is particularly beneficial in areas that experience voltage drops. The reactive power supplied is proportional to the excitation voltage and can be expressed as in Eqn. (11)

$$Q_{Supply} = \frac{V_{exc}^2}{X_s} \tag{11}$$

Reactive power absorption: In the case of an under-excited synchronous condenser, where the rotor's field current is less than optimum, it absorbs reactive power, assisting in rectifying the unwanted excess of reactive power in some areas of the grid. It is expressed as in Eqn. (12)

$$Q_{absorb} = \frac{V_{exc}^2}{X_s} \tag{12}$$

Where Q_{Supply} is the reactive power supplied (in vars), Q_{absorb} is the reactive power absorbed (in vars), V_{exc} is the excitation voltage, X_s is the synchronous reactance.

The starting current of a synchronous condenser is typically higher than the rated current due to the need to bring the rotor to synchronous speed. This is commonly expressed as in Eqn. (13)

$$I_{start} = \frac{V_{rated}}{X_s} \tag{13}$$

Where I_{start} is the Starting current, V_{rated} is the Rated voltage of the machine, X_s is the Synchronous reactance.

The voltage regulation of a synchronous condenser can be defined as the difference between the no-load and full-load terminal voltages, expressed as a percentage. This Eqn. (14) helps evaluate the ability of the synchronous condenser to regulate the voltage and maintain stability during load fluctuations.

$$\text{Voltage Regulation}(\%) = \frac{V_{no-load} - V_{full-load}}{V_{full-load}} \tag{14}$$

A good advantage of SCs is that they have short-term voltage stabilization. Most often, this happens at the time of a fault or sudden load change. Rotating mass in the synchronous condenser adds inertia to the system for stabilization of the grid frequency. This inertia is very important to the grid during oscillations or disturbances because it postpones the rate of change of frequency, thus giving the control systems more time to react and stabilize the system. The inertia can be quantified as in Eqn. (15)

$$H = \frac{J\omega^2}{2} \tag{15}$$

Where:

- H = Inertia constant (in seconds),
- J = Moment of inertia (in kg·m^2),
- ω = Angular speed (in rad/s).

This equation is used to model the dynamic response of SCs to sudden changes in the grid, as the rotational mass helps dampen grid frequency fluctuations.

SCs are normally used at strategic locations in the grid where maximum benefits can be derived. Typically these locations are in regions with weakened voltage conditions or at points where reactive power compensation is required to support voltage regulation. These would include

Voltage Sensitive Areas: Some areas of the grid may experience frequent voltage drops that occur near large industrial loads or at the far end of long transmission lines; SCs are often used in these places to provide support to voltage by supplying reactive power in time.

Grid Stability Improvement: These condensers are also located where grid stability needs to be improved, such as at substations or nodes where there is frequent fluctuation of voltage or where a sudden loss of reactive power (owing to a fault or significant load change) can destabilize the system.

To achieve an effective integration of the SCs with the overall power system, they need to be very carefully planned and executed for the right operation. Typically, these are connected with a transformer to the grid and must be designed such that they have compatible voltage levels as well as current requirements with the system.

SCs are today part of modern power systems often integrated with Supervisory Control and Data Acquisition (SCADA) systems. Real-time monitoring and control provide the operator with the option of excitation adjustments of the condenser on real-time conditions of the grid. Operators can therefore monitor parameters like voltage levels, reactive power output, and machine health and can carry out the necessary adjustments to guarantee optimised operation.

SCADA Integration: It allows through real-time monitoring through SCADA systems the dynamic control of reactive power compensation according to the actual requirements of the system by adjusting the excitation levels. It also enhances and maintains safe and efficient synchronous condenser operations.

Automatic Voltage Control: AVRs are installed on the SCs such that it continuously adjusts excitation to maintain the desired voltage level at the point of connection. This is dynamic voltage control, especially needed in places where the probability of change in voltage levels tends to be high. It is expressed in Eqn. (16)

$$E_f = E_{set} + K_f.\Delta V \tag{16}$$

Where E_f is the field excitation voltage, $E_{set}$is the set point voltage, K_f is the feedback constant, ΔV is the change in voltage at the point of connection.

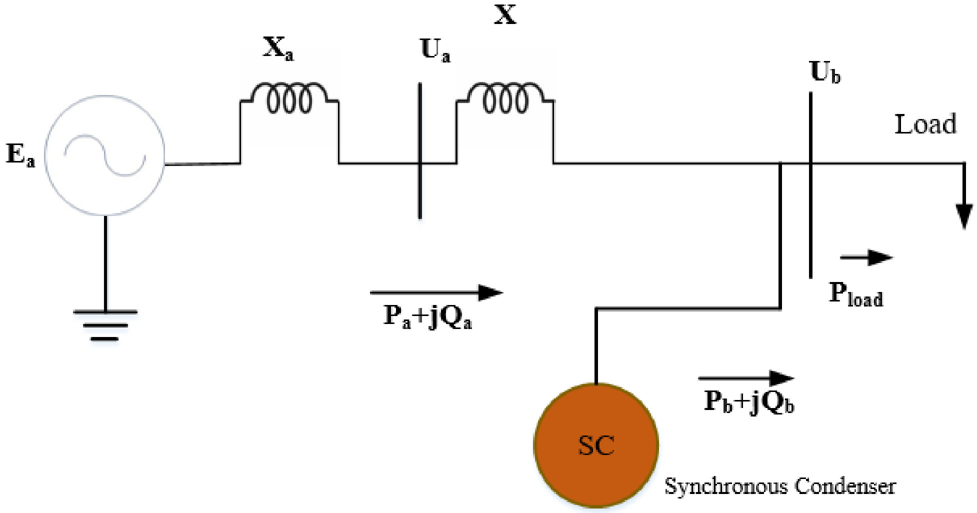

Figure 3: Synchronous Condenser-Single phase

Figure 3 shows the SCs support the maintenance of the stability of the voltage level in the grid and increases the inertia of the grid. The contribution of a capability to provide or absorb reactive power allows them to help stabilize the grid at the time of transient disturbance. Their rotating mass has the added value of system inertia. However, their introduction into the grid requires attention to operational considerations including excitation control, starting current, mechanical losses, and cooling needs. Due to proper placing and combining SCs with state-of-the-art supervisory systems like SCADA, a tremendous improvement is brought in terms of grid power's reliability and effectiveness.

3.2.3 Static and Dynamic Behavior in Reactive Power Management

Static and dynamic behaviors are distinguishable in reactive power management as part of the power grid.

Static behavior represents situations where the grid operates steadily, under predictable and relatively steady load profiles. In this setup, capacitor banks are predominantly used as shunt elements to inject fixed reactive powers, enhancing voltage stability and PFs. These banks are controlled by manual or automated ON/OFF switching mechanisms, which supply a constant amount of reactive power. This method is effective in reducing line losses, improving efficiency, and stabilizing voltage under normal load conditions. Static solutions are well-suited for grids with stable and predictable voltage regulation needs.

Dynamic behavior addresses the system's response to rapid changes in load, generation, or grid disturbances. Real-time reactive power adjustment can be made using capacitor banks installed with Thyristor-Switched Capacitors since capacitors can be turned into the circuit in real-time. SCs are dynamic sources and sinks of reactive power based on dynamic adjustments of their excitation levels to provide real-time voltage stabilization and to dampen frequency fluctuations through additional rotational inertia. These dynamic solutions are important for grid stability and efficient operation, particularly in transient events that can cause voltage dips or surges and sudden changes in loads. Therefore, with a combination of both static and dynamic strategies, the overall performance of the grid would be stable and reliable over an enormous range of scenarios.

4. RESULTS AND DISCUSSION

The study's results clearly indicate that the effects of reactive power compensation on improving system performance are considerable. Improvements in voltage stability, reduction in transmission losses, and PF optimization were among the results. From the analysis, it is evident that compensation techniques have effectively minimized the deviation of voltages so that the system remains within the desired limits. Simultaneously, a remarkable loss reduction across the power grid illustrates that the compensation of local reactive power is a method enhancing its efficiency. Such results can further be validated by additional and graphical representations of performances alongside their comparison.

4.1 Distribution of Active and Reactive Power and Cumulative Power Analysis

Figure 4 shows the Annual power losses with different configurations of the grid. This figure clearly indicates that with compensation devices, the losses are greatly reduced. Annual losses are at 4,500 MWh when there is no compensation, and with DCBs, the loss reduces to 1,800 MWh, and to 1,200 MWh with SCs. This is a clear indication of how efficient SCs are in minimizing both active and reactive power losses.

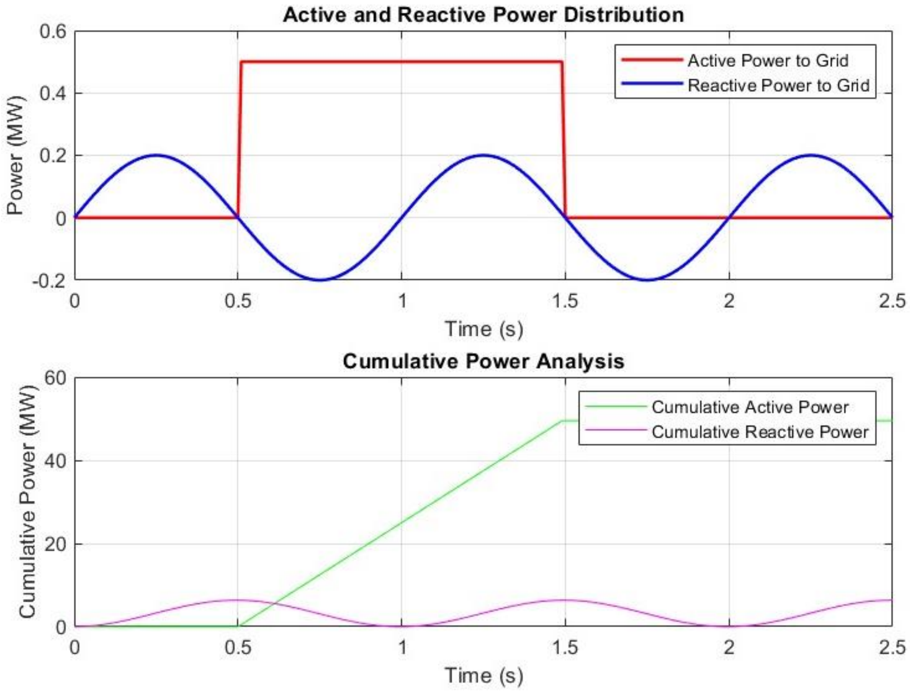

Figure 4: Annual Power Losses across Grid Configurations with and without Compensation Devices

Figure 5 shows the source voltage profile versus time. It is sinusoidal, typical of an AC system. The amplitude of the voltage is constant, showing a stable power supply from the source. The figure is essential for determining the quality of the voltage fed into the system, minimizing distortion, and ensuring proper operation. A stable voltage profile is thus needed for the satisfactory operation of the electrical equipment connected to the system.

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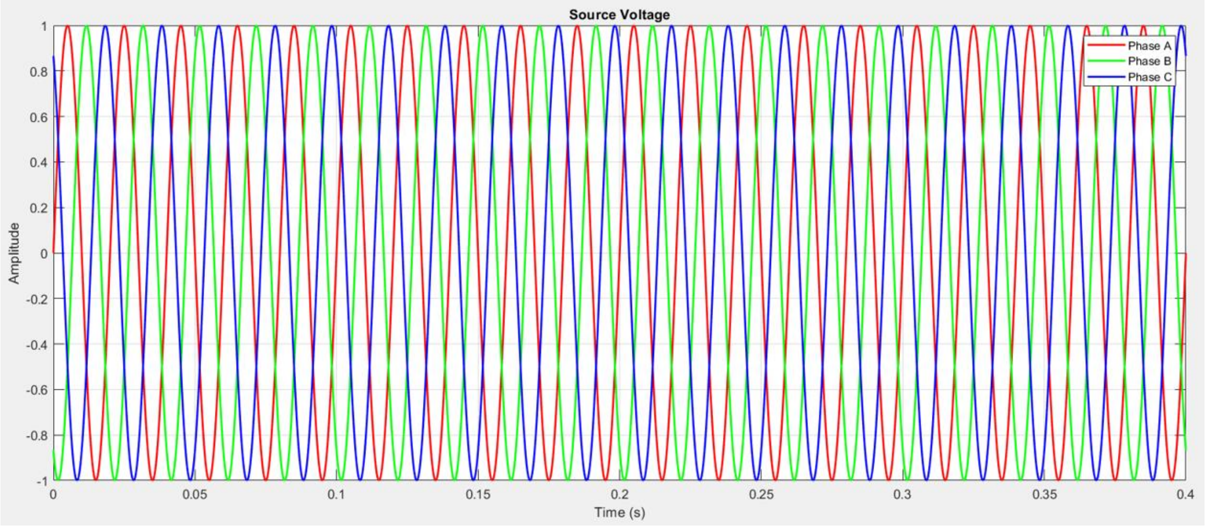

Figure 5: Source Voltage

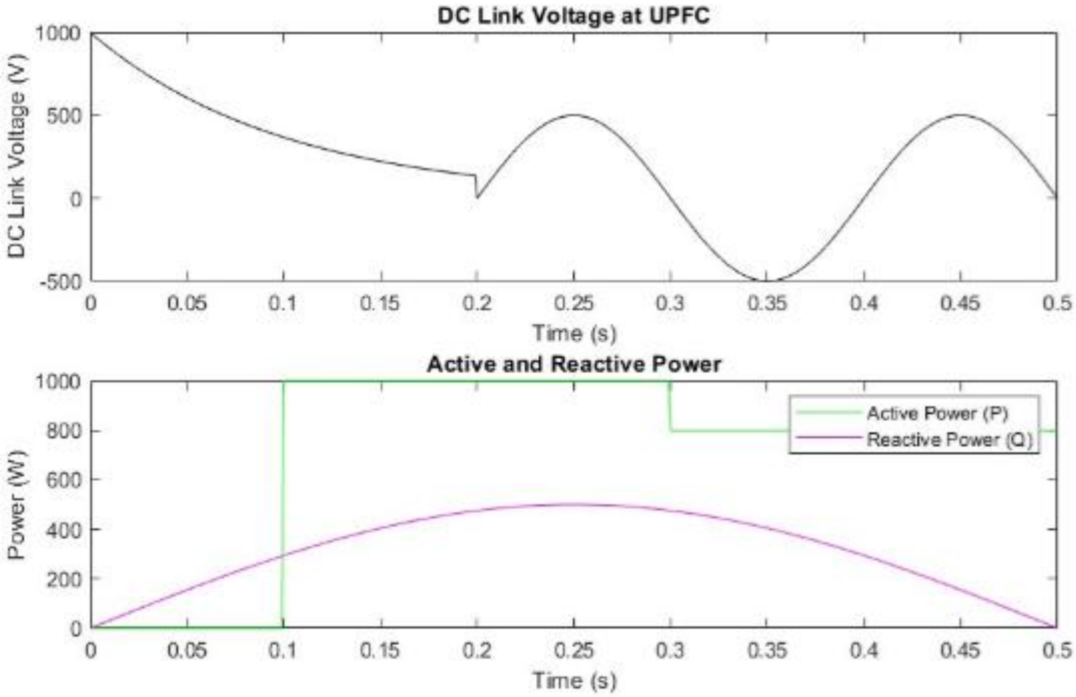

Figure 6: Performance Analysis of UPFC in Voltage and Power Regulation

Figure 6 demonstrates the dynamic performance of the UPFC for the control of voltage and power. The upper plot gives the dynamic response of DC link voltage; after oscillation, it reaches stabilization, which implies the ability of the UPFC in the control of voltage. In the lower plot, P and Q are plotted. The active power is delivered steadily, but the reactive power increases to provide support to the voltage. UPFC effectively stabilizes the voltage and manages the power flow under various loading conditions, which verifies its relevance in enhancing grid reliability and combating instability.

4.2 Reactive Power Compensation Efficiency

Efficiency of the compensation system in delivering the necessary reactive power. The effectiveness of the system can be measured in terms of how much of the reactive power demand it is able to compensate. Table

2 shows the reactive power compensation efficiency for different grid configurations: without compensation, with DCBs, and with SCs.

Table 2: Reactive Power Compensation Efficiency

Grid Configuration	Reactive Power Compensation (%)	Voltage Deviation (±%)	PF Improvement (%)
Without Compensation	0	10	0
With DCBs	80	±3	10
With SCs	95	±1	15

4.3 Voltage Profile Improvement

Table 3 depicts voltage profiles at two significant nodes, one near the source of renewable generation and another near a load centre. The voltage profile is defined here as the range of the deviation of voltage from its nominal value at the said nodes. Node 1 will experience larger voltage fluctuations, because of the variability in renewable generation, whereas Node 2 will have more stable voltage without compensation.

Table 3: Voltage Profile Improvement at Key Nodes

Grid Configuration	Node 1: Near Renewable Source	Node 2: Near Load Center
Without Compensation	85% to 90%	87% to 92%
With DCBs	95% to 98%	97% to 99%
With SCs	98% to 100%	99% to 100%

4.4 Impact of Reactive Power Compensation on PF

Table 4 provides the enhancement of PF with various compensations schemes. Average PF shows the total PF at the end. Peak PF is defined as the maximum PF while operating on the grid.

Table 4: Impact of Reactive Power Compensation on PF

Grid Configuration	PF (Without Compensation)	PF (With DCBs)	PF (With SCs)
Average PF	0.85	0.95	0.97
Peak PF	0.88	0.96	0.98

Figure 7 illustrates voltage regulation across time under three scenarios. Without reactive power management, voltage levels remain the lowest, indicating significant instability. DCBs and SCs improve voltage regulation, with the latter showing the best performance, particularly during peak and off-peak hours.

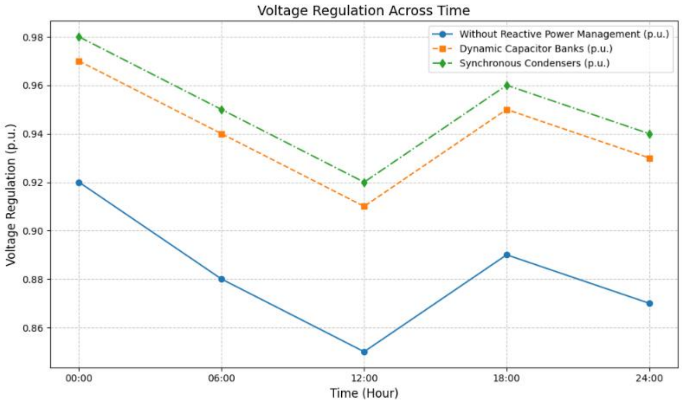

Figure 7: Voltage Regulation across Time

Figure 8 compares three scenarios: without management, with DCBs, and with SCs, for the three grid nodes during penetration of renewable energy sources. Without management, voltage levels are below the optimal, which means instability. Adding DCBs improves voltage levels but keeps them lower than optimal. SCs exhibit the best performance and offer a voltage close to 1.0 p.u. ensuring the stability of the grid. This presents the effectiveness of SCs in solving problems caused by renewable energy through integration.

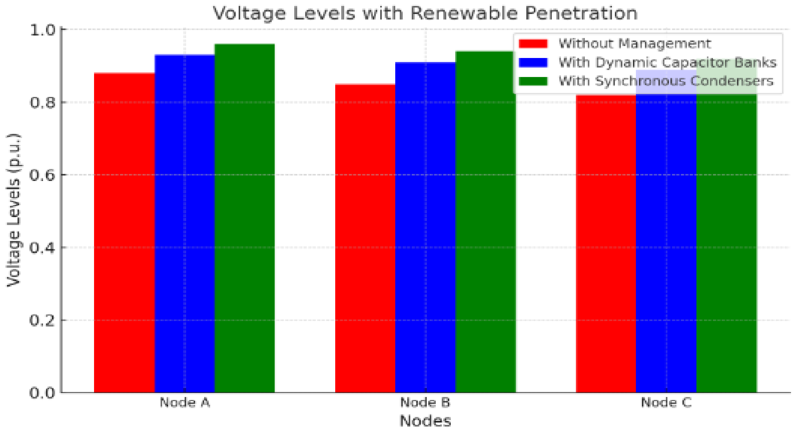

Figure 8: Voltage Level with Renewable Penetration

Table 5 compares how the grid's transient response to faults is under different compensation strategies - recovery time and stability after disturbances. Voltage Recovery refers to the amount by which the voltage returns to its nominal value upon clearing the fault. Recovery Time refers to the time it takes the grid to recover to normalized steady-state voltages after a disturbance.

Table 5: Transient Response during Faults

Fault Scenario	**Grid Configuration**	**Recovery Time (Seconds)**	**Voltage Recovery (±%)**
Sudden Load Increase	Without Compensation	5	±8%
	With DCBs	2	±2%
	With SCs	1	±1%
Short Circuit Fault	Without Compensation	8	±10%
	With DCBs	4	±4%
	With SCs	2	±1%

Figure 9 illustrates frequency stability across different load change events. Frequency deviation is highest without support, highlighting the system's vulnerability. DCBs and SCs significantly reduce deviations, with SCs providing the most stability under all events.

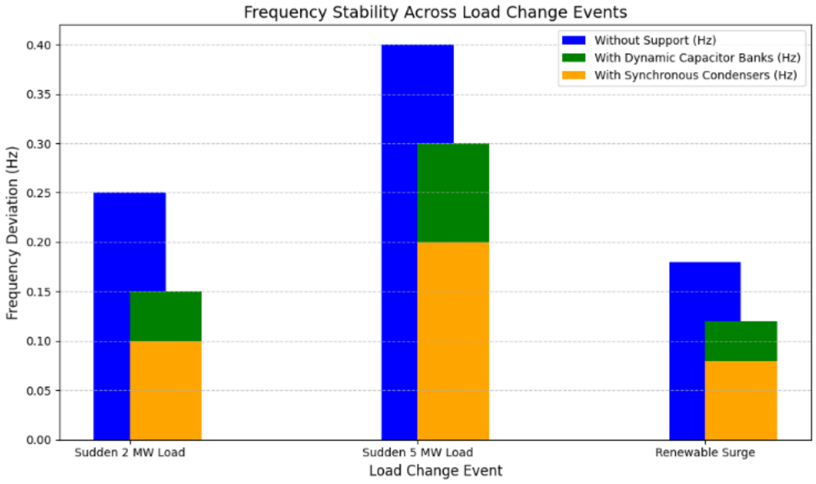

Figure 9: Frequency Stability across Load Change Events

Figure 10 illustrates energy loss and improvement percentages for three scenarios. Without reactive power management, energy losses are highest, serving as the baseline. DCBs show the greatest improvement in reducing energy losses, followed by SCs, which also demonstrate notable efficiency gains.

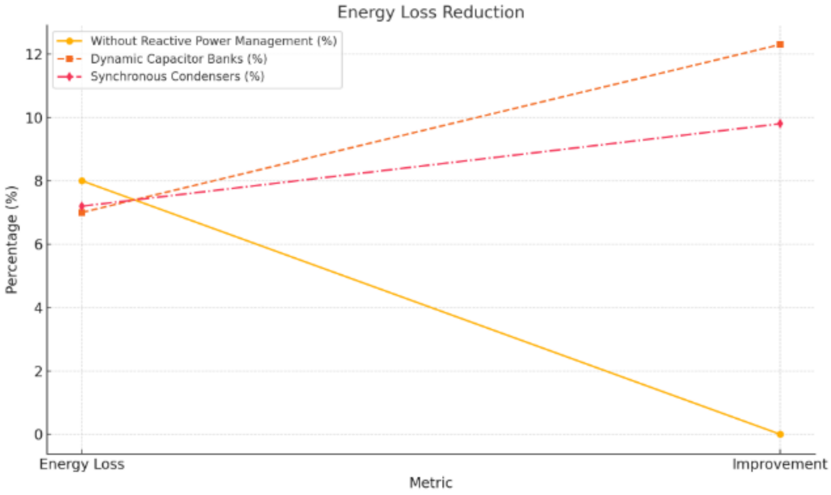

Figure 10: Energy Loss Reduction

Figure 11 showcases the power losses in the system under various scenarios. It highlights the baseline losses without reactive power management, which are significantly higher compared to scenarios with implemented support measures. DCBs and SCs demonstrate a clear reduction in losses, with SCs providing marginally better performance, emphasizing their role in enhancing system efficiency.

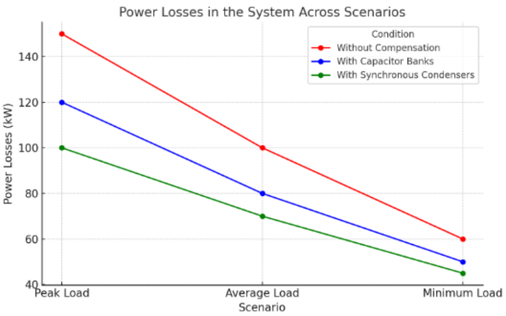

Figure 11: Power Losses in the System

Figure 12 compares these on a graph, with the added message of balance between cost and performance for optimal grid stability. This efficiency advantage makes it more suitable for grids with high penetration of renewable sources, stability and precision being critical parameters. However, the relatively lower costs of capacitor banks make this more practical for regions with budget constraints or lesser reactive power demands.

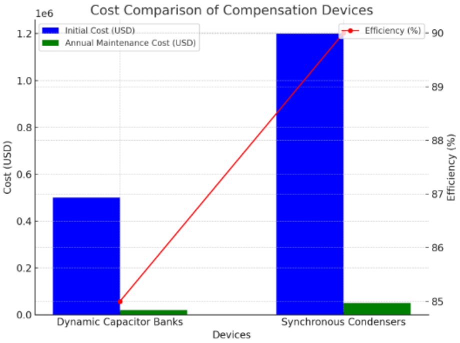

Figure 12: Cost Comparison of Compensation Devices

Table 6: Comparison of Reactive Power Compensation Approaches-Proposed Method vs. Existing Studies

Paper	Key Findings	Contribution to the Field	Comparison with Proposed Approach	Limitations
Shin et al. [20]	Enhanced ESS control methods to smooth out power output from RES and minimize voltage fluctuations.	Proposed a reactive power control enhancement for ESS to improve power quality, especially in grids with high renewable energy penetration.	The proposed approach focuses more on DRPC with SCs and capacitor banks. While Shin et al. focus on ESS, both studies aim at minimizing voltage fluctuations. However, the proposed approach integrates two physical devices for a more direct	The method still struggles with reactive power integration in dynamic systems, requiring further tailoring, which aligns with challenges in optimizing synchronization of reactive power solutions in complex grids.

			reactive power solution.	
Fan et al. [22]	Investigated the integration of SCs for improving system stability and voltage regulation in grids with renewable energy integration.	The paper analyzed the role of SCs in enhancing system inertia and reducing voltage fluctuations.	Similar to the proposed approach, Fan et al. also work with SCs. However, the proposed approach integrates both capacitor banks and SCs, providing more flexible compensation across various grid conditions.	Faces high operational costs, mechanical wear, and challenges with optimal sizing, similar to the proposed paper's recognition of challenges in real-world deployment.
Afrasiabi et al. [19]	Proposed a multi-agent energy management framework for microgrids to minimize energy loss and operating costs. The framework uses deep learning to forecast energy demands, market prices, and renewable generation.	Introduced a multi-agent approach that uses deep learning for forecasting and distributed optimization for energy management in microgrids.	The proposed approach differs significantly, focusing on DRPC rather than multi-agent systems. The proposed approach integrates specific technologies (capacitor banks and SCs) for immediate reactive power control and voltage regulation.	The framework's complexity, especially in practical applications, could lead to issues with implementation, including accuracy of historical data and computational requirements for forecasting. The proposed approach does not face these challenges but relies on physical reactive power compensation devices.
Proposed Method	DRPC using capacitor banks and SCs for voltage stability, power loss minimization, and integration with renewable energy.	Combines both capacitor banks and SCs to provide a flexible, scalable solution for reactive power compensation in complex and dynamic grid environments.	The approach integrates both capacitor banks and SCs for a more comprehensive solution. Unlike other studies, it focuses on dynamic compensation, addressing the needs of modern grids with high renewable energy penetration and fluctuating demand.	The complexity of optimal placement and sizing, especially in large-scale and fast-changing grid conditions.

Table 6 highlights the advantages and disadvantages of the proposed approach in DRPC with capacitor banks and SCs. Similar studies may focus on specific components like ESS or individual reactive power compensation devices, but the proposed approach considers both capacitor banks and SCs for flexibility and scalability. However, like existing studies, there are challenges to optimizing system performance, cost management in complex and dynamic grid environments, and also ensuring real-time adaptability.

4.5 Discussion

This work depicts the significant improvement in the power grid, particularly with the integration of renewable energy, through the implementation of reactive power compensation. DRPC approaches like DCBs and SCs achieve enhancement of voltage stability and lower transmission losses with optimized PFs. Therefore, the results further demonstrate why reactive power compensation is needed in grids to operate efficiently as well as compare various real compensation approaches.

Results Interpretation: DCBs and SCs increased the efficiency of reactive power compensation to 80% with capacitor banks and 95% with SCs, whereas without compensation, it was 0%. This resulted in lower voltage deviations: ±1% with SCs and ±10% without compensation. SCs are more stable and effective, especially in highly renewable energy grids where voltage fluctuations are a common occurrence. PF improvements were also recognized, 10% in the use of capacitor banks and 15% with SCs brought the peak PF to 0.98 with SCs and only to 0.88 without compensation. All these results support the idea that reactive power compensation is a way of optimizing grid performance with variable loads.

Theoretical Implications: DRPC techniques - including capacitive banks and SCs - provide more insight into the relevance of voltage stability in modern grids. These results reinforce this theory that reactive power compensation helps mitigate some problems introduced by the variability of renewable energy.

Practical Implications: In practice, deploying SCs and capacitor banks improves grid stability, especially where renewable energy generation is high in the grid. The devices reduce voltage deviation and improve PF and make the grid more reliable and efficient, thus lowering transmission loss and improving voltage profiles. These can help optimize performance and bring down costs for grid operators. For large-scale grids mainly comprising renewable energy sources, SCs might find better benefits in terms of network voltage stability due to fluctuations in energy generation.

Limitations: The effectiveness of a compensation device may also vary depending on the grid size, and location, among others. Additionally, in large grids, compensation devices may have challenging optimal placement and sizing.

5. CONCLUSION AND FUTURE WORKS

This study successfully demonstrated the optimization of power grid efficiency through DRPC utilizing capacitor banks and SCs. Implementation of these technologies together ensures that the critical challenges presented by voltage instability and minimizing power loss have been better addressed in the context of an increasingly modernized grid, specifically in those that are becoming more penetrated by renewable energy. The proposed approach brought about stability in the grids while it significantly improved on the reactive power management efficiency by ensuring power transmission systems have optimum operation. Based on these findings, a capacitor bank and synchronous condenser may be combined as potential DRPC solutions as it will prove to be feasible and reliable. Such integration will also provide an easily scalable and cost-effective yet sustainable methodology for keeping voltage stability in a power network with reduced loss in operational procedures, necessary for better reliability and resilience in grids. In the same sense, these technologies highlight the capability of evolving to transform the landscapes of energy so that energy sources will be produced cleaner and sustainably as well. DRPC will enable successful application on modern grids as they struggle with complexities. The present research thus establishes the foundation from which further innovation will proceed in the pursuit of increased performance for grids and greater energy sustainability for the future.

Future research may look into using ML with dynamic reactive power systems for real-time predictions and decisions. Testing these systems in large smart grids may also help in understanding how these systems behave in different scenarios. Integration of technologies like STATCOMs and battery storage will improve the efficiency of the grid. Cost studies and real-world trials will be important to check if these solutions are practical and cost-effective.

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