Improving Voltage Stability in Sabha Medium Voltage Network Using FACTS Techniques: A Comparative Study between STATCOM and SVC

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Abstract

Voltage stability faces significant challenges due to the increasing demand for electricity and reliance on long transmission lines, particularly in medium-voltage networks in southern Libya. This study focuses on the 66 kV Sabha network, which suffers from voltage instability caused by dependence on northern power generation sources and high reactive power losses. Using the NEPLAN software, the effectiveness of two FACTS devices, namely the Static Var Compensator (SVC) and the Static Synchronous Compensator (STATCOM), was evaluated in improving voltage stability.

The study considered three scenarios: without compensation, with SVC, and with STATCOM. The results showed that both devices significantly improve voltage stability and reduce power losses, with STATCOM demonstrating superior dynamic response and overall efficiency. These findings highlight the importance of advanced compensation technologies in ensuring the stability and reliability of power delivery under challenging operational conditions.

Keywords: Voltage Stability, Medium Voltage Networks, FACTS Devices, Static Synchronous Compensator (STATCOM), Static VAR Compensator (SVC)

تحسين استقرار الجهد في شبكة الجهد المتوسط في سبها باستخدام تقنيات FACTS: دراسة مقارنة بين STATCOM وSVC

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الملخص

يواجه استقرار الجهد تحديات كبيرة بسبب الطلب المتزايد على الكهرباء والاعتماد على خطوط النقل الطويلة، خاصة في شبكات الجهد المتوسط بجنوب ليبيا. تركز هذه الدراسة على شبكة سبها بجهد 66 كيلو فولت، التي تعاني من عدم استقرار الجهد نتيجة الاعتماد على مصادر توليد الطاقة الشمالية وخسائر الطاقة التفاعلية العالية. باستخدام برنامج NEPLAN، تم تقييم فعالية جهازين من تقنيات FACTS وهما المعوض المتزامن الثابت (SVC) والمعوض المتزامن الديناميكي، (STATCOM) في تحسين استقرار الجهد.

تناولت الدراسة ثلاثة سيناريوهات: بدون تعويض، باستخدام SVC وباستخدام STATCOM. أظهرت النتائج أن كلا الجهازين يحسنان استقرار الجهد بشكل ملحوظ ويقللان من خسائر الطاقة، مع تفوق STATCOM في الاستجابة الديناميكية والكفاءة الإجمالية. تؤكد هذه النتائج أهمية تقنيات التعويض المتقدمة في ضمان استقرار وموثوقية توصيل الطاقة في الظروف التشغيلية الصعبة.

1. Introduction

The rapid growth in electricity demand, combined with economic and environmental pressures driving the interconnection of power systems, has pushed modern electrical networks to operate closer to their stability limits. Among the critical challenges faced by these systems is voltage collapse, a phenomenon that occurs when the system cannot sustain acceptable voltage levels under high-loading conditions. Voltage collapse is characterized by a precipitous decline in bus voltages, often resulting in significant load losses and, in severe cases, large-scale blackouts. Historically, major incidents of voltage collapse have caused billions of dollars in equipment damages and service disruptions, affecting millions of customers [1].

Voltage stability issues stem from the intricate interactions between three primary subsystems:

1. Power Sources: Their active and reactive power generation capabilities, locations, control strategies, and dynamic responses.

2. Loads: Their magnitude, geographical distribution, sensitivity to voltage variations, and dynamic behavior.

3. Transmission Networks: The infrastructure connecting generators to loads, encompassing impedance, topology, and operational constraints [2].

In Libya, particularly in the southern region, the power network heavily depends on generation sources located in the northern areas. This reliance on long transmission distances significantly amplifies voltage stability challenges. The 66 kV medium-voltage network, including the Sabha ring, plays a crucial role in the southern power system. During peak load periods, several key issues are observed:

- A sharp decline in voltage levels across critical buses.
- Sudden voltage collapse leading to load losses.

Traditional methods to address these challenges, such as capacitor switching, increasing reactive power generation, and implementing load-shedding programs, often lack the dynamic responsiveness needed to manage rapid voltage fluctuations and load variations. These limitations highlight the urgent need for advanced solutions that provide real-time support for voltage stability.

As power systems evolve under deregulated markets, one of the primary challenges is ensuring a transmission network that can deliver contracted power between any supplier and consumer over extensive geographic areas. This challenge is exacerbated by continuously varying market-driven power flows and contractual arrangements.

In this context, advanced technologies are critical to maintaining the reliable and secure operation of power systems. Among these, Flexible AC Transmission System (FACTS) devices, such as Static Synchronous Compensator (STATCOM) and Static Var Compensator (SVC), stand out due to their ability to provide rapid and effective responses to system events, enhance power transfer capability, and improve the quality of power delivery [3-4].

This study explores the application of FACTS devices, specifically STATCOM and SVC, to tackle voltage instability in the 66 kV medium-voltage network in Sabha. By performing a comparative analysis, the study seeks to determine the most effective solution for enhancing voltage stability and ensuring reliable network performance under challenging conditions.

This research is particularly significant for Libya, where the reliance on long transmission distances and the absence of renewable energy integration exacerbate voltage stability issues.

The study aims to achieve the following objectives:

1. Investigate Voltage Stability: Analyze the factors contributing to voltage instability in the Sabha 18 KM ring network.

2. Integrate Advanced Compensation Technologies: Evaluate the effectiveness of STATCOM and SVC in providing fast and dynamic reactive power compensation.

3. Compare STATCOM and SVC Performance: Conduct a comparative analysis to determine the superior technology for maintaining stable voltage profiles.

4. Simulate and Analyze Using NEPLAN: Use NEPLAN software to model the network and simulate various load conditions to validate the performance of the proposed solutions.

1.2 Voltage Stability

Voltage stability refers to the ability of a power system to maintain steady voltage levels across all buses under normal operating conditions and after being subjected to disturbances such as faults, sudden load changes, or generation outages. It is a critical aspect of power system operation, as voltage instability can lead to severe consequences, including voltage collapse, which may trigger widespread blackouts.

This phenomenon arises when the system is unable to supply sufficient reactive power to maintain voltage levels, particularly in areas with high load demand or long transmission distances. The balance of reactive power is therefore a fundamental factor in ensuring voltage stability, as reactive power is crucial for maintaining the magnetic fields in transformers, generators, and other electrical equipment. An imbalance between reactive power generation and consumption can result in voltage drops, system inefficiencies, and even instability.

The relationship between reactive power (Q) and voltage (V) at a specific point in the network can be mathematically expressed as:

$$Q = \frac{V}{X}(V_S - V)$$

Where Q is the reactive power demand (MVAR), V is the voltage at the load point (kV), V_S is the voltage at the source (kV), and X is the reactance between the source and the load (Ohms). This equation illustrates that as the voltage at the load point (V) decreases, the reactive power demand (Q) increases significantly. If this demand is not adequately compensated, voltage instability or even collapse may occur.

The main factors affecting voltage stability include reactive power balance, system configuration, and the capacity of voltage support devices such as FACTS controllers. In medium-voltage networks, challenges like long transmission distances, high load demand, and integration of renewable energy sources further complicate voltage stability. To enhance voltage stability, devices such as STATCOM and SVC can be employed, as they provide dynamic reactive power compensation and improve the voltage profile under varying load conditions. This study evaluates the role of these devices in improving voltage stability in the Sabha medium-voltage network [5]

1.3 Challenges of Medium Voltage Networks

Medium-voltage networks face numerous technical and operational challenges that directly affect their stability and efficiency. One of the primary challenges is voltage instability, which arises due to the long distances involved in transmitting power between generation stations and consumption areas, as is the case in southern Libya. Relying on generation stations in the north results in lower voltage levels in southern networks and increased energy losses due to the length of transmission lines and the high demand for reactive power. This issue is further exacerbated during peak load periods, where voltage drops significantly across critical buses, leading to potential instability and system inefficiencies.

The deterioration of infrastructure is another significant challenge for these networks. Most of the transmission lines, transformers, and circuit breakers in older networks are unable to meet the growing load demands. This deterioration leads to higher fault rates, increased maintenance costs, and a general decrease in network efficiency.

Furthermore, load imbalance is a major issue in medium-voltage networks. Uneven load distribution across different areas of the network stresses certain parts, increasing the likelihood of faults and reducing the lifespan of equipment.

Another important challenge is fault management. Detecting and isolating faults over long distances requires advanced protection and monitoring systems. The absence of such systems leads to delays in service restoration and increased energy losses.

Energy losses resulting from transmission line resistance and poor power factors are an ongoing challenge in Libyan networks. These losses reduce network efficiency and increase operational costs.

Although Libya does not currently rely heavily on renewable energy sources, the future integration of renewables could introduce new challenges for the grid. The intermittent nature of solar and wind energy may cause fluctuations in power quality and voltage levels, necessitating significant upgrades to handle these variations [6].

1.4 Sabha 18kM Substation (220/66 KV) Network

The Sabha (220/66 KV) network is one of the vital transmission rings in southern Libya. It serves as a primary connection between power sources and local distribution networks. Due to the long transmission distances from the northern generation stations, the Sabha network experiences significant reactive power shortages, resulting in voltage instability during high-demand periods. As the load increases throughout the day, voltage magnitudes gradually decline, pushing the system closer to its stability limits.

1.5 FACTS Devices

Flexible AC Transmission Systems (FACTS) are advanced technologies based on power electronics designed to enhance the performance of electrical power networks. These systems play a crucial role in addressing the challenges faced by Libyan power networks, such as increasing energy demand, long transmission lines, and the heavy reliance on power generation stations in the northern regions to supply energy to the south. FACTS improve voltage stability, increase transmission capacity, and reduce energy losses, making them essential for achieving efficient and stable power networks in Libya.

FACTS systems consist of various devices, including the Static Var Compensator (SVC), which enhances voltage stability by injecting or absorbing reactive power in a static manner, making it suitable for medium- and low-voltage networks.

The Static Synchronous Compensator (STATCOM) is a more advanced device that provides dynamic reactive power compensation, improving voltage stability during load changes or sudden faults. Additionally, the Unified Power Flow Controller (UPFC) offers comprehensive control over both active and reactive power flow, making it one of the most versatile and effective FACTS devices. Another notable device is the Thyristor Controlled

Series Capacitor (TCSC), which improves system stability and reduces energy losses by controlling series reactance.

FACTS systems contribute to voltage stability by injecting or absorbing reactive power to maintain voltage levels within permissible limits, particularly during peak demand or disturbances. They also help increase transmission capacity by alleviating congestion in transmission lines, enabling the delivery of energy over long distances without compromising stability. Furthermore, FACTS reduces energy losses by improving the power factor, minimizing the reactive current in the network. Additionally, they enhance the dynamic stability of the system by mitigating transient oscillations and improving performance during sudden load changes or faults.

In the Libyan power network, which heavily relies on northern generation stations to supply energy to the south, FACTS systems provide an effective solution for improving voltage stability and reducing losses caused by the long transmission distances. Studies show that using devices like SVC and STATCOM in medium-voltage networks can significantly enhance network performance, particularly in areas experiencing voltage imbalances due to high loads or extended transmission distances [7-8]

1.5.1 SVC (Static VAR Compensator)

According to the IEEE definition, a Static VAR Compensator (SVC) is "a static VAR generator whose output is varied to exchange capacitive or inductive current to maintain or control specific parameters of the electric power system, typically bus voltages." In simpler terms, a static VAR generator becomes an SVC when equipped with specialized external controls that enable it to perform the desired compensation of the transmission line, based on operating requirements and prevailing system variables.

The primary purpose of the static VAR compensator is usually the rapid control of voltage at weak points in a network. Installation may be at the midpoint of interconnection lines or in load areas.

The SVC is an advanced device used to improve voltage stability in electrical networks. It works by compensating for reactive power losses through the dynamic control of the reactive power flow between voltage and current in the network [9-10].

Components of SVC

An SVC generally consists of:

- Variable Capacitors and Reactors: Used for reactive power compensation.
- Electronic Control System: Manages the dynamic flow of reactive power.

The control system enables the SVC to regulate the flow of reactive power between voltage and current in the network, as illustrated in Figure (1).

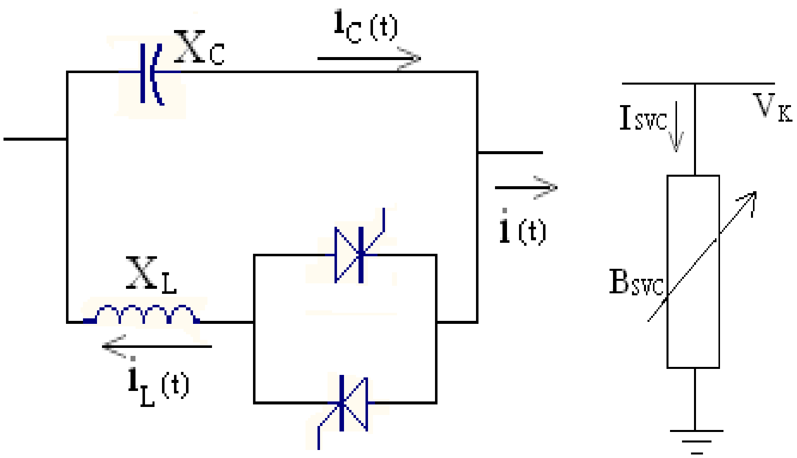

Figure (1): Equivalent circuit of SVC

The main goal of using SVC in medium-voltage networks is to maintain stable voltage across the network under various operating conditions, especially during high-load periods or rapid load fluctuations. SVC provides a fast response to voltage variations, which helps to improve network stability by either supplying or absorbing reactive power dynamically. This enhances the ability of the network to respond to sudden load changes or operational conditions [5].

Practical Applications

SVCs are widely used in various applications to improve the stability of electrical networks, including:

- Voltage stabilization in long transmission lines.
- Reducing electrical oscillations.

- Improving power factor.

1.5.2 STATCOM (Static Synchronous Compensator)

The Static Synchronous Compensator (STATCOM) is a crucial device within the Flexible AC Transmission Systems (FACTS) that enhances voltage stability in electrical networks. Unlike traditional systems that rely on controllable reactors and switched capacitors, the STATCOM employs a Voltage Source Converter (VSC) to regulate voltage levels effectively. This advanced design enables precise control over reactive power, providing significant performance improvements [11].

The operation of a STATCOM is based on its ability to manage the reactive power exchanged with the grid. When the system voltage is low, the STATCOM generates reactive power in a capacitive mode to boost voltage levels. Conversely, when the voltage is high, it absorbs reactive power in an inductive mode to maintain balance. This functionality is achieved through the VSC, which connects to the secondary side of a coupling transformer. By varying the magnitude of the converter's output voltage relative to the grid voltage, the STATCOM can effectively stabilize the system as illustrated in Figure 2.

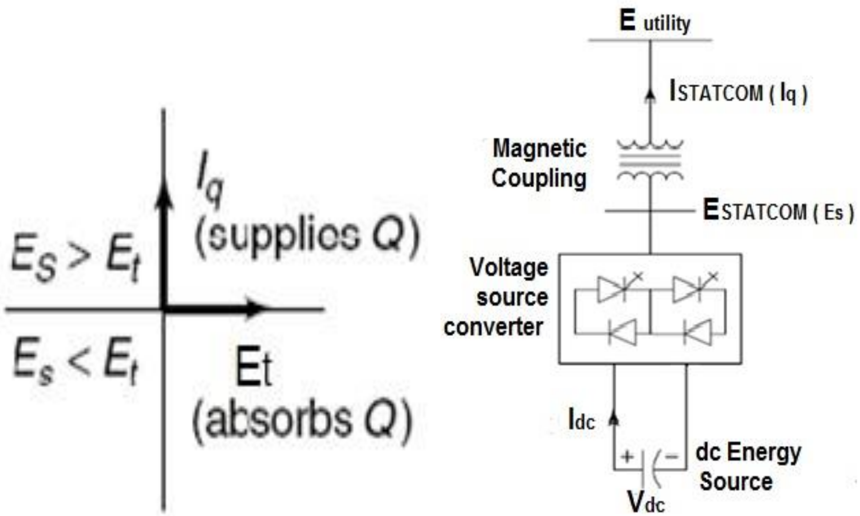

Figure 2: The STATCOM principle diagram

The STATCOM is an advanced compensation technology used to improve voltage stability in electrical networks, and it represents an evolution of the traditional SVC. The key difference between SVC and STATCOM is that STATCOM uses synchronous power conversion technology with advanced power electronics, allowing it to provide faster and more precise reactive power compensation than SVC [10-11].

STATCOM operates by injecting or absorbing reactive power through integrated electronic circuits. It is particularly beneficial in networks experiencing significant voltage fluctuations due to heavy loads or sudden changes in generation. STATCOM has greater flexibility in controlling voltage under multiple operating conditions, making it an ideal choice for medium-voltage networks like the Sabha 66 kV network in southern Libya.

1.5.3 Comparison between (SVC) and (STATCOM)

A comparison between Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) reveals significant differences in their functionality and performance. SVC is a static device that utilizes variable capacitors and inductors to regulate reactive power and stabilize voltage levels. Its operation involves adjusting reactance to either inject or absorb reactive power. However, SVC has a relatively slower response to voltage fluctuations, making it more suitable for networks that require steady reactive power support rather than dynamic adjustments.

On the other hand, STATCOM is a more advanced and dynamic device that uses power electronics to provide reactive power. Unlike SVC, STATCOM offers faster and more efficient responses to rapid voltage changes, making it ideal for modern power systems facing frequent load variations or disturbances. Additionally, STATCOM has a wider control range for reactive power, allowing it to maintain voltage stability more effectively under varying load conditions.

In summary, while SVC is suitable for applications requiring static reactive power improvement, STATCOM is the preferred choice for networks demanding quick and dynamic voltage stabilization, particularly in medium-voltage systems like the Sabha network analyzed in this study [9].

1.6 General Overview of National Grid

The Libyan national power grid with its three sectors; Generation, Transportation, and Distribution up to end users are operated and maintained by GECOL.

Grid operating voltage ranges from UHV 400 kV, HV 220 kV, MV at 66 kV, Sub. MV 30 kV and distribution level at 11 kV. The average demand growth rate over the past three decades was 8% per annum.

Accordingly, the total lengths of the cables and overhead transmission lines according to the operating voltage as shown in Table 1

Table 1: Underground Cables and Overhead Transmission Lines.

The Voltage (kV)	Overhead Transmission (Km)	Underground Cables (Km)
400	2290	….
220	13706	154
66	14311	165
30	11142	5084

Total numbers of Substations and installed capacity according to the operating voltage as shown in Table 2.

Table 2: Substations and Installed Capacity

The Voltage (KV)	Numbers Of Substations	Installed Capacity (MVA)
400	13	9600
220	87	19006
66	195	4359
30	461	13914

The figure (3) illustrates the geography of Libyan UHV & HV transmission power grid.

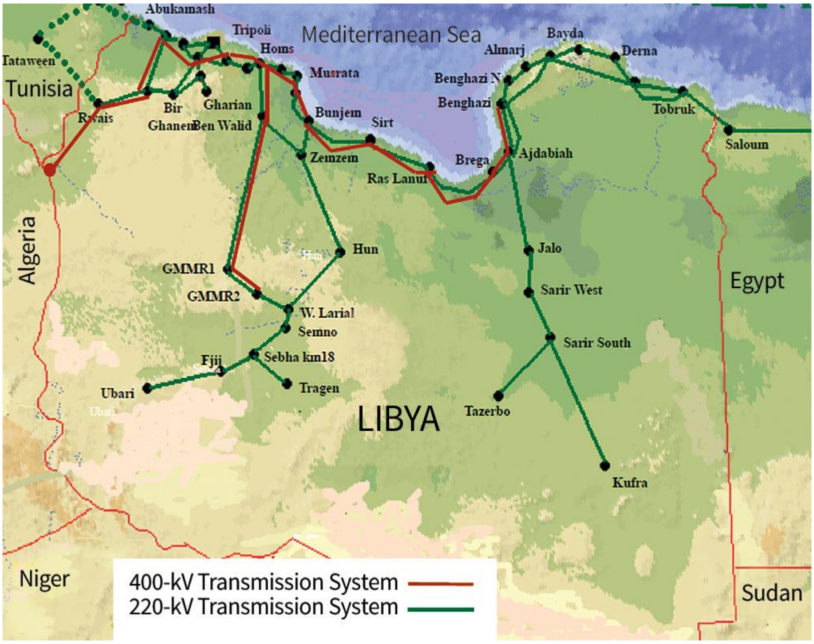

Figure 3: The Geography of Libyan UHV & HV Power Grid.

2. Methodology

The study focused on the medium-voltage network in Sabha city, located in southern Libya, operating at 66 kV. The objective was to enhance voltage stability, which faces significant challenges due to a heavy reliance on power generation sources in the northern part of the country, long transmission lines, and increased energy losses. NEPLAN software was utilized as the primary analytical tool to evaluate the network's performance and assess the impact of different compensation techniques on improving voltage stability and reducing energy losses.

The study concentrated on two key FACTS technologies: the Static Var Compensator (SVC), which enhances voltage stability by controlling reactive power flow, and the Static Synchronous Compensator (STATCOM), known for its dynamic capability to handle rapid voltage fluctuations. The analysis was conducted under three main scenarios:

1. The first scenario examined the network without compensation to assess its current state.

2. The second scenario evaluated the performance with SVC.

3. The third scenario analyzed the network with STATCOM to compare its effectiveness with the other cases.

The methodology involved inputting detailed network data into NEPLAN software, which included specifications for lines, generators, and loads. Simulations were conducted for each scenario, and key performance indicators were measured and analyzed. These indicators included voltage stability, energy losses, and dynamic response under various operational conditions. Finally, the results from the three scenarios were compared to determine the most efficient technology based on its ability to improve voltage stability, reduce energy losses, and enhance the overall operational efficiency of the network of the network.

2.1 Case Study

The study utilized real data obtained from GECOL to analyze the medium voltage network in the Sabha 18 KM ring. The analyzed network includes Sabha main 220/66/11 kV substation, which consists of multiple 220 kV incoming feeders and several outgoing 66 kV and 11 kV lines.

Sabha 18 kM ring is serviced by several 66/11 kV substations, while the 66 kV network extends to supply nearby villages in the southern region.

The single line diagram of the power system under study as shown in Figure 4

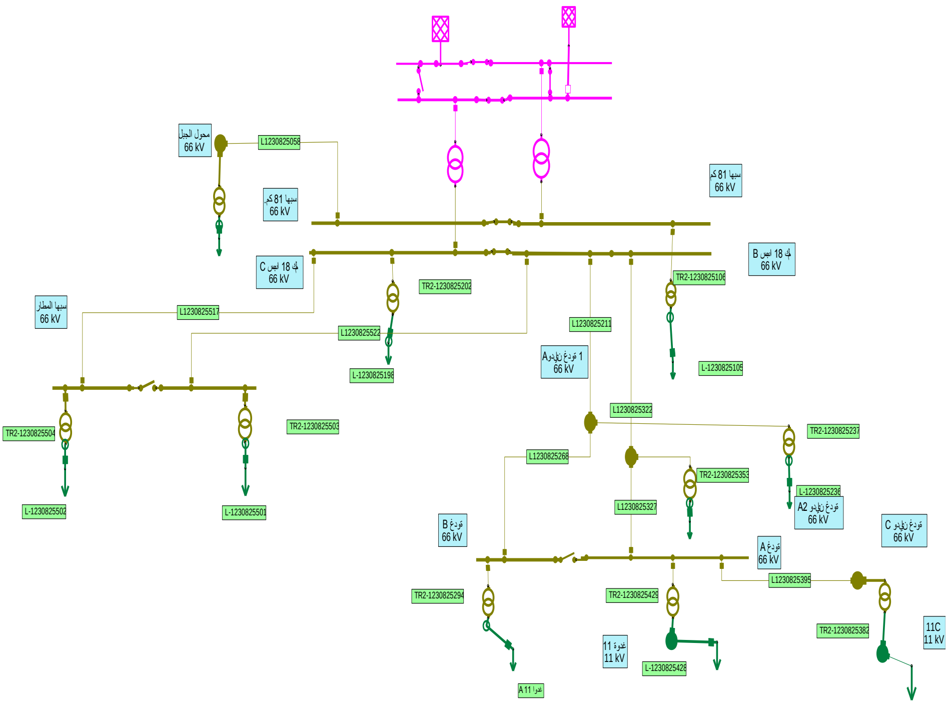

Figure 4: Single line diagram 66KV of Distribution system

The Newton Raphson's Load flow analysis method is used in this work. A NEPLAN based program was developed for the power flow analysis of the Sabha (220/66 KV) network without Facts and with SVC, STATCOM to explore the effects of these FACTS devices on the voltage collapse of the Sabha 66KV ring.

Through the simulation, several locations were tested for the placement of SVC and STATCOM. Among these, the Wadiyan Ghadwa 66/11 Substation yielded the best results in enhancing voltage stability across the network. As it, demonstrated superior performance compared to other tested locations.

a) First Scenario (Normal Operation)

In this case, the network operates in a steady state (without FACTS), with 220 kV substations connected to the Sabha network. The results of the load flow analysis it presented in Table 1.

Table 1: Network Load Flow with Existing Case

	From Area/Zone	To Area/Zone	P Loss	Q Loss	P Imp	Q Imp	P Gen	Q Gen
			MW	MVar	MW	MVar	MW	MVar
1	Network		2.564	31.41	85.464	82.785	85.464	82.785
2	Area 1		2.564	31.41	0	0	85.464	82.785
3	Zone 1		2.564	31.41	0	0	85.464	82.785
4								
5	Un		P Loss Li	Q Loss L	P Loss T	Q Loss		
6	kV		MW	MVar	MW	MVar		
7	66		1.296	2.176	0.41	8.03		
8	220		0	0	0.849	21.203		
9								
1	Overloads							
1	Nodes (lower	%						
1	B-1230825201	89.9						
1	A1 وديان غدوة	88.27						
1	B-1230825514	88.24						
1	A2 وديان غدوة	87.69						
1	B غدوة	86.43						
1	A غدوة	85.82						
1	C وديان غدوة	85.39						
1	B-1230825297	84.77						
2	B-1230825356	82.65						
2	11 غدوة	82.63						

The bus voltages of regional substations in the existing case as obtained from the simulation are represented graphically in the Figure (5).

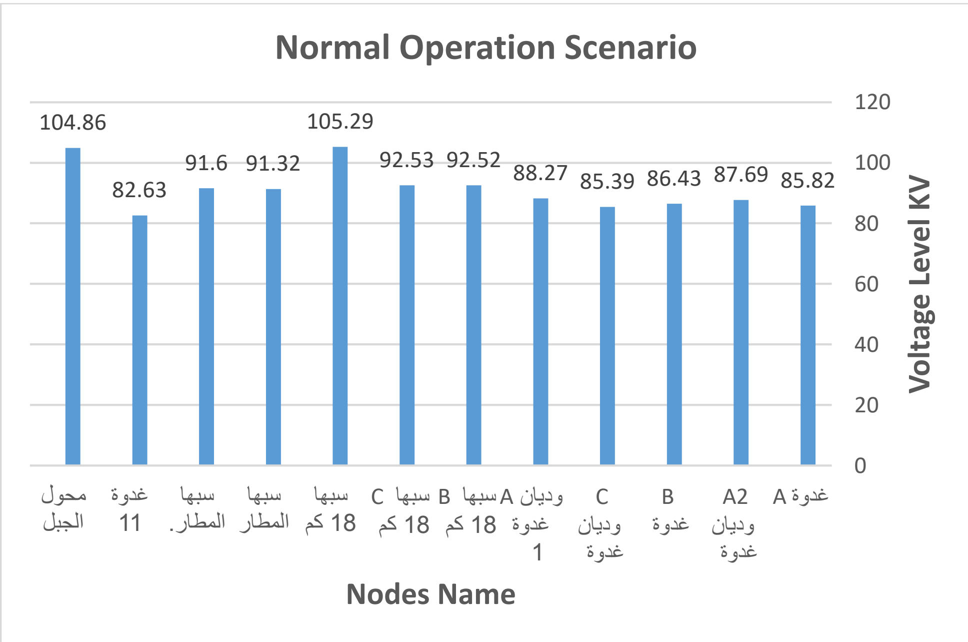

Figure (5): Bus Voltages for Normal Operation Scenario

In the first scenario, (Normal Operation) the voltage levels at several buses are critically low, indicating the presence of voltage collapse. Voltage collapse occurs when the power system cannot maintain stable voltage levels due to high reactive power demand and insufficient voltage support. For instance, Bus Gdwaa A voltage drops to 85.82 volts, far below acceptable operational limits. Similarly, other buses, such as Wdyann Gdwaa C bus (85.39 volts) and Bus Gdwaa 11 (82.63 volts), also show dangerously low voltage levels.

This scenario reflects a system under stress, where the lack of reactive power compensation leads to a cascade of voltage drops, particularly at buses farther from the source or under high load conditions. The system is on the verge of instability, and further increases in load or disturbances could lead to a complete voltage collapse, potentially causing widespread outages.

b) Second Scenario (With SVC)

In the second scenario, the simulation analyzes the base network with an SVC inserted into it. The resulting load flow is shown in Tables 2.

Table 2: Network Load Flow with SVC Installed

	From Area/Zone	To Area/Zone	P Loss	Q Loss	P Imp	Q Imp	P Gen	Q Gen
			MW	MVar	MW	MVar	MW	MVar
1	Network		1.927	23.262	84.827	59.969	84.827	59.969
2	Area 1		1.927	23.262	0	0	84.827	59.969
3	Zone 1		1.927	23.262	0	0	84.827	59.969
4								
5	Un		P Loss L	Q Loss L	P Loss T	Q Loss		
6	kV		MW	MVar	MW	MVar		
7	66		0.952	0.942	0.35	6.851		
8	220		0	0	0.619	15.469		
9								

The bus voltages of regional substations in the case of installing the SVC as obtained from the simulation are represented graphically in Figure 6.

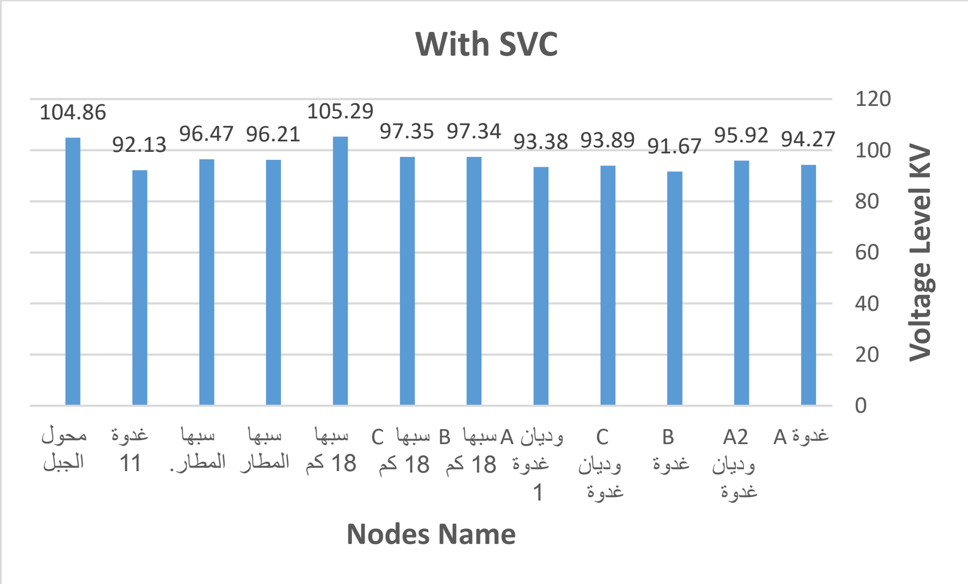

Figure (6): Bus Voltages for Second Scenario

In the second scenario, where the Static Var Compensator (SVC) is applied, the voltage levels at the buses show significant improvement compared to the first scenario. The SVC provides dynamic reactive power support, helping to stabilize voltage levels across the network. For instance, at Bus Gdwaa A, the voltage rises to 94.27 volts, which is a marked improvement from the critically low level of 85.82 volts observed in the first scenario. Similarly, Bus Wdyann Gdwaa C and Bus Gdwaa 11 experience voltage levels of 93.89 volts and 92.13 volts, respectively, indicating enhanced stability.

The application of SVC effectively mitigates the risk of voltage collapse by addressing the reactive power demand in the system. However, while the voltage levels are brought closer to acceptable operational limits, they remain slightly below the ideal range, suggesting that the SVC provides partial but not complete stabilization under high load conditions. This highlights the importance of further optimization or exploring alternative compensation technologies to ensure full voltage stability.

C) Third Scenario (With STATCOM)

In the Third scenario, the simulation analyzes the base network with a STATTCOM inserted into it. The resulting load flow is shown in Table 3.

Table 3: Network Load Flow with STATCOM Installed

	From Area/Zone	To Area/Zone	P Loss	Q Loss	P Imp	Q Imp	P Gen	Q Gen
			MW	MVar	MW	MVar	MW	MVar
1	Network		1.219	16.583	0	0	0	0
2	Area 1		1.219	16.583	0	0	99.119	43.101
3	Zone 1		1.219	16.583	0	0	99.119	43.101

The bus voltages of regional substations in the case of installing the STATCOM as obtained from the simulation are represented graphically in Figure 7.

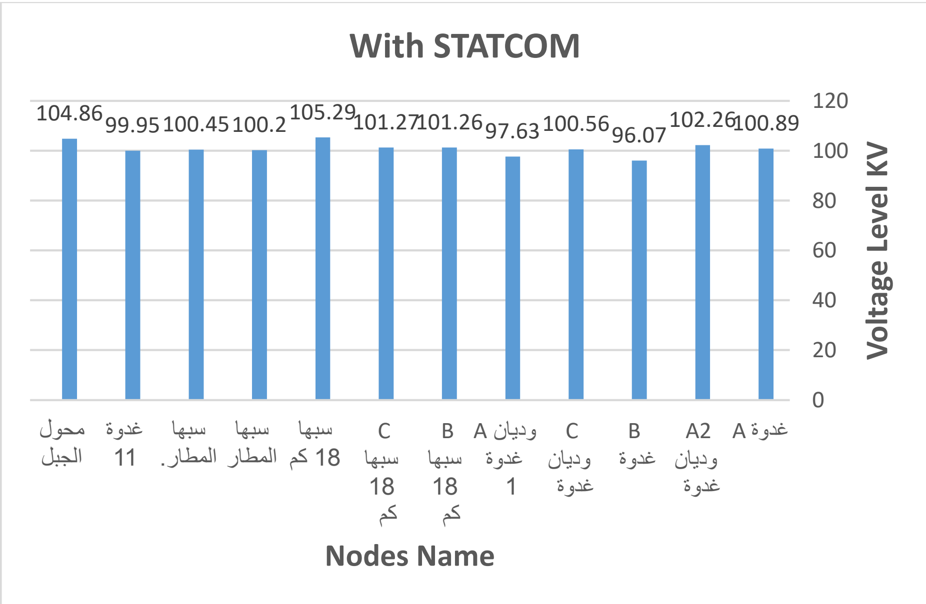

Figure (7): Bus Voltages for Third Scenario

In the third scenario, where Static Synchronous Compensator (STATCOM) is applied, the voltage levels achieve the most significant improvement among all scenarios. STATCOM, with its advanced reactive power compensation capabilities, ensures stable voltage levels even under high load conditions. At Bus Gdwaa A, the voltage increases to 100.89 volts, which is well within acceptable operational limits. Similarly, Bus Wdyann Gdwaa C and Bus Gdwaa 11 show voltage levels of 100.56 volts and 99.95 volts, respectively, demonstrating a highly stable system.

The superior performance of STATCOM compared to SVC can be attributed to its faster response time and higher efficiency in providing reactive power support. This scenario not only eliminates the risk of voltage collapse but also ensures that the system operates within optimal voltage ranges, making STATCOM a more effective solution for maintaining voltage stability in stressed power systems.

2.2 Comparison of the Three Scenarios:

In this section, a comparison between the three scenarios is presented to evaluate the performance of the network under different conditions:

1. without Compensation
2. with SVC
3. with STATCOM

The comparison focuses on two key aspects:

Voltage Stability: Examining the voltage levels across different buses in the network.

Power Losses: Comparing active and reactive power losses in each scenario.

The following figures provide a clear visualization of the results.

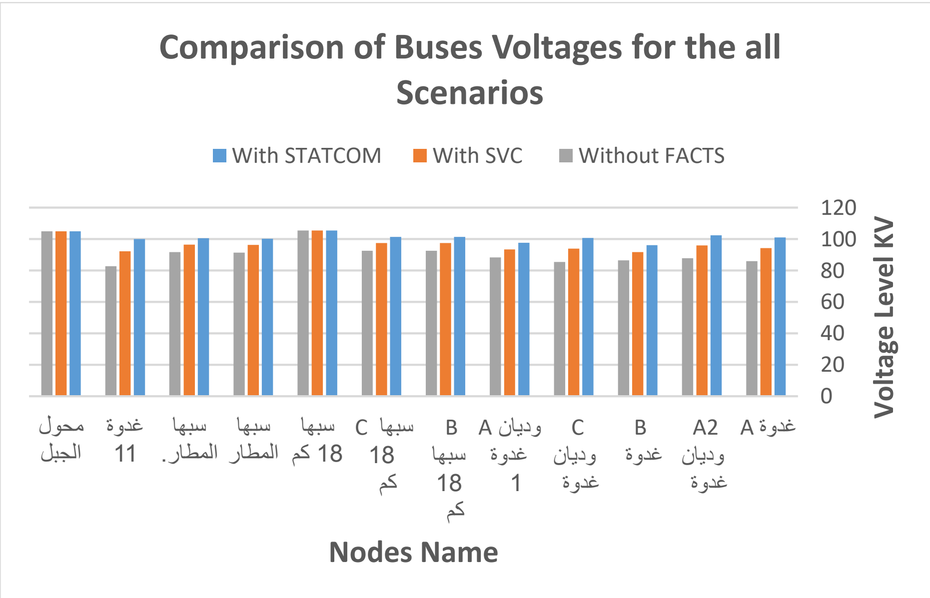

Figure (8): Comparison of Voltages buses across Buses for the Three Scenarios

Figure (8) demonstrates that adding compensation devices (SVC and STATCOM) significantly improves voltage levels across the buses compared to the scenario without compensation. STATCOM provides better voltage stability than SVC, particularly on buses with lower voltage levels. These results emphasize the importance of dynamic compensation technologies in enhancing voltage stability within the network.

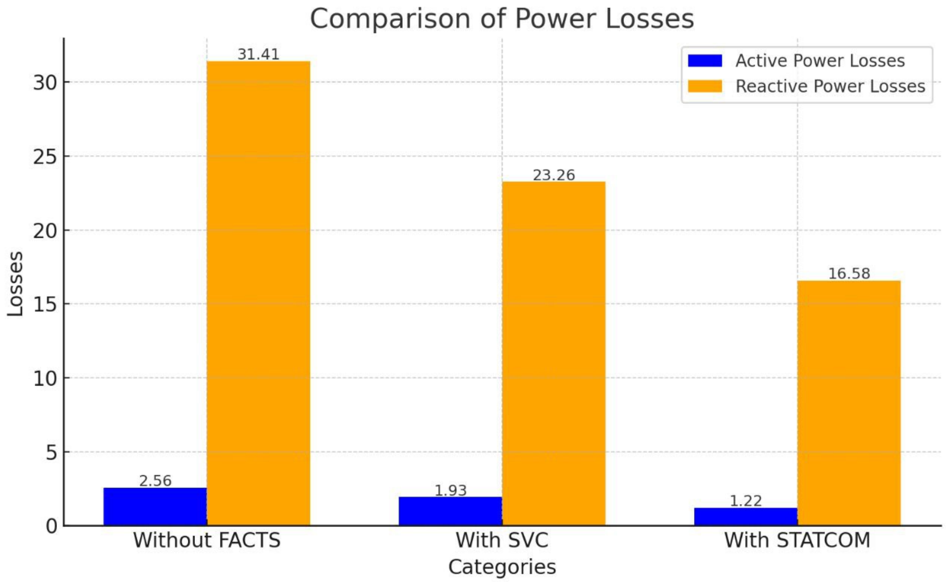

Figure (9): Comparison of Active and Reactive Power Losses for the Three Scenarios

The chart shows that STATCOM and SVC reduce active and reactive power losses compared to the scenario without compensation. STATCOM performs better than SVC, achieving the lowest power losses, making it the most efficient option. It is noticeable that reactive power losses are highest in the scenario without compensation, highlighting the critical role of compensation technologies in improving network efficiency.

3. Conclusion:

The study concludes that voltage instability in Sabha 66 kV medium-voltage network can be effectively mitigated using advanced FACTS devices. Through simulations and analysis, it was observed that both STATCOM and SVC significantly improve voltage stability and reduce power losses.

However, STATCOM demonstrated superior performance in dynamic response, achieving faster and more precise compensation compared to SVC.

The results indicate that STATCOM is the optimal choice for maintaining stable voltage profiles under varying load conditions, offering higher efficiency and reliability. This underscores the importance of adopting advanced compensation technologies like STATCOM in medium-voltage networks, particularly in regions facing challenges such as long transmission distances and dependency on remote generation sources. Implementing these technologies ensures a more robust, stable, and efficient power system capable of meeting increasing electricity demands. Future research could explore hybrid solutions or other FACTS devices to further optimize network performance.

4. Future Recommendations

Integrating FACTS Technologies like STATCOM and SVC:

Utilizing these technologies to improve voltage stability, provide dynamic reactive power compensation, reduce oscillations, and ensure network stability under various operating conditions is recommended.

Utilizing Artificial Intelligence and Machine Learning Systems:

AI and ML systems can monitor and analyze real-time network data, enabling predictive maintenance and proactive decision-making to enhance performance.

Upgrading Network Infrastructure:

Modernizing transmission lines and transformers with advanced technologies can reduce energy losses and improve network efficiency, particularly in areas with high load demands.

Enhancing Preventive Maintenance Programs:

Implementing maintenance plans based on continuous equipment monitoring can reduce unexpected failures and extend the lifespan of network components.

Preparing for Renewable Energy Integration:

Although renewable energy sources are currently absent in the Libyan grid, future planning for their integration requires appropriate infrastructure, such as energy storage systems, to maintain network stability when renewables are introduced.

These recommendations align with the study's findings and provide a roadmap for addressing the challenges faced by medium-voltage networks in Libya. Future research could explore hybrid solutions or alternative FACTS devices to further optimize network performance and adapt to evolving energy demands.

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