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Performance Evaluation of Static Synchronous Compensator and Static VAR Compensator Under Fault Conditions

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ABSTRACT

This paper aims to investigate the critical role of reactive power in maintaining voltage stability in electrical power systems, focusing on a 186 km, 230 kV transmission line between the Debre Berhan and Combolcha II substation, in the Amhara Region of Ethiopia. While alternating current (AC) is predominantly used for the generation, transmission, and distribution of electrical energy, it presents challenges such as the need for reactive power to support inductive loads and maintain voltage levels. This study underscores the necessity of efficient voltage regulation to prevent equipment overheating, reduce transmission losses, and avoid voltage collapse. The objective of this research is to improve the voltage profile of the transmission line using Flexible AC Transmission System (FACTS) devices, specifically the Static VAR Compensator (SVC) and the Static Synchronous Compensator (STATCOM). Through simulations, the performance of the transmission line is evaluated in terms of reactive power compensation and voltage regulation. The results demonstrate that STATCOM outperforms SVC under normal operating conditions by maintaining the transmission voltage closer to the reference level and providing more robust reactive power support. In fault scenarios, STATCOM shows superior performance, exhibiting less voltage drop and higher reactive power compensation capability compared to SVC.

1. INTRODUCTION

Electrical energy is generated, transmitted, distributed, and utilized in the form of alternating current (AC) unless there are a few unique circumstances. When electrical energy is ready for use, it is transmitted from the generating stations to the consumers. The generating stations are located far away from load centers. The transmission system is the network that transports and distributes electric power from the generating stations to the substations. The demand for electric power has been rising significantly for a long time, but power transmission over electrical transmission networks is limited [1]. These restrictions result from power transfer capacity limit, thermal loading of conductors, balancing supply, allowing a certain voltage level, and preserving network stability. So, the power system is operating lower than its maximum capacity. The result is that the power transmission systems do not operate as efficiently as they could. Building a new transmission line is one of the numerous options to address the growing issue of electricity transmission capacity; however, this is neither feasible nor practicable. Over the past 20 years, researchers have been working to create new algorithms and models for power system stability that use Flexible AC Transmission System (FACTS) devices for dependable, quick, and continuous management of the transmission system's power flow. These devices have been used in a variety of power system security, damping ratio enhancement, and economical power dispatch applications to enable the provision of power to customers without going against system limits [2].

While transmitting AC power, one of the drawbacks is that reactive power must be supplied in addition to active power. It's known that real power is the amount of power being used to turn on motors, light bulbs, charge phones, etc., and is something that we are all more accustomed to. The purpose of reactive power is to establish electromagnetic fields that are necessary for inductive loads like transformers and motors to operate effectively. Additionally, it serves to maintain an interrupted supply of real power by controlling the voltage levels in transmission lines.

Maintaining voltage levels on the transmission system depends on reactive power. Voltage also contributes to the stability of power flows in the electric system. Nearly every system component, including the generation, transmission, and distribution systems as well as the loads themselves, generates or consumes reactive power. Electric generators have historically produced or absorbed reactive power to maintain a constant voltage level, a process known as "voltage support." Generators that support voltage frequently experience thermal losses, which diminish their capacity to produce "actual" power. The effects of failing to maintain voltage on the electric system, however, are urgent since voltage collapse can seriously harm generation, transmission, and distribution equipment and cause severe cascading blackouts. Yet, genuine power generation is sacrificed when generators are required to produce or absorb reactive power to support voltage. Voltage control is serious for the operation of electrical power equipment, to reduce transmission losses, and to maintain the system's stability.

Managing reactive power and voltage control are necessary for the following reasons. Electrical equipment is made to function at a range of voltage levels, typically within 5% of the nominal voltage. Many types of equipment perform badly at low voltages, including light bulbs that give less illumination, motors that can overheat and even become damaged, and some electronic devices that won't work. High voltages have the potential to harm equipment and reduce its lifespan. Reactive-power flows must be reduced in order to increase the amount of real power that can be transported through a crowded transmission line. Generating reactive power might restrict a generator's ability to produce real power. Real power losses are incurred when reactive power is moved on the transmission network.

The transmission system is a nonlinear consumer of reactive power. The system generates reactive power at light loading conditions that must be absorbed, and the system consumes a large amount of reactive power at heavy loading. The system consists of various pieces of equipment, each of which can fail at any time. As a result, the system is designed to withstand the loss of any single piece of equipment while continuing to operate without affecting any customers. In order to overcome these existing challenges in voltage control, a portion of the reactive supply is needed to compensate variable reactive-power demands and maintain voltages within acceptable ranges. In order to respond to emergencies, an electrical system must therefore retain reactive power reserves in addition to real power reserves. So that the power system can maintain a flat voltage profile even in the occurrence of current and contingency conditions by managing reactive power. This allows it to reduce real-power losses and flow congestion while also maintaining adequate voltages throughout the transmission and distribution system. Shunt and series compensation are types of reactive power compensation. There are several goals for every application. Inductive or capacitive shunt reactive compensation is possible. Generally, compensation is typically capacitive. Both inductive and capacitive reactive compensations are implemented at a transmission substation.

In order to control the voltage magnitude, quality, and to improve the system stability, shunt compensation has been used [3]. Shunt-connected reactors are consuming the reactive power to reduce the line over-voltages, while shunt-connected capacitors are supplying the reactive power to the transmission line to reduce low voltages. Shunt compensation can be used from the load level to the transmission level. It can be capacitive (leading) or inductive (lagging) reactive power. The drastic growth of people is causing serious problems in our system, as it increases the demand for power. As power demand continues to rise, electrical networks are increasingly exposed to higher stresses and potential overload. Such operating conditions often lead to challenges, including voltage instability, reduced controllability, and limitations in loadability. Traditional corrective measures—such as phase-shifting transformers and on-load tap-changing transformers—were commonly employed to address these issues. However, their relatively slow response, limited flexibility, and lower reliability restrict their effectiveness in modern power systems. To overcome these drawbacks, FACTS were introduced. FACTS devices, based on advanced power electronics, enhance system performance by improving controllability, increasing loadability, regulating power flow, and supporting voltage stability. They also help mitigate various stability constraints that conventional equipment cannot adequately handle. FACTS applications are diverse: shunt controllers are used to support voltage, series controllers regulate power flow and reduce transmission losses, and combined (hybrid) configurations offer broader functionality. With their rapid response and high flexibility, FACTS technologies are expected to play a significant role in upgrading transmission networks and improving overall system efficiency. Chou et al. [4] developed a MATLAB/Simulink model of a Static Synchronous Compensator (STATCOM) for reactive power compensation. A STATCOM is a shunt-connected FACTS device designed to enhance the voltage profile of a transmission network. It operates through a voltage-source inverter (VSI) linked to a DC-capacitor. By providing dynamic reactive power support, the STATCOM helps reduce power losses, improve the power factor, and stabilize the voltage profile within the transmission system. This paper used the Pulse Width Modulation (PWM) technique as a control strategy using the dq0 transformation and also studied different results with different percentages of compensation.

Adepoju and Tijani [5] provided an overview of the Nigerian power network and its existing compensation practices, particularly in relation to voltage drops and power losses. Their study underscores the limitations of conventional control devices currently deployed in the system and highlights the advantages of FACTS devices as more effective alternatives. The review revealed that Nigeria's 330 kV/132 kV transmission lines still rely heavily on traditional compensation methods. The authors further demonstrated that installing FACTS devices at strategic points characterized by low voltages and high-power losses could significantly enhance transmission capacity and improve power delivery to the national grid. Agashe et al. [6] employed a STATCOM to enhance power quality, power factor, voltage profile, and reactive power compensation. They developed a vector-control strategy aimed at improving the system's power factor, achieving results that brought the power factor close to unity. The proposed strategy demonstrated superior performance and faster dynamic response compared with existing methods, confirming the effectiveness of STATCOM-based vector control in power factor correction. Berhe [7] investigated the Sululta–Addis Ababa South-II transmission substation, which lies along the northwest–southeast corridor of Addis Ababa. The study identified significant voltage drops at multiple bus terminals, resulting in reduced power transfer capability. To mitigate this issue, a Thyristor-Switched Capacitor (TSC), a shunt-connected FACTS device, was recommended as a suitable compensation method for improving the substation's voltage profile. Shaheen et al. [8] examined the optimal placement of a Unified Power Flow Controller (UPFC) using evolutionary optimization techniques. They demonstrated that the UPFC is highly effective for regulating power flow and maintaining bus voltage levels, thereby improving system stability, reducing losses, and increasing transfer capability. Genetic algorithms and particle swarm optimization were applied to validate the proposed approach using the IEEE 14-bus test system. The results confirmed the UPFC as one of the most powerful FACTS devices for power-flow control. Vandana and Verma [9] conducted a comprehensive analysis of various FACTS controllers—including the Thyristor-Controlled Series Capacitor (TCSC), Thyristor-Switched Series Capacitor (TSSC), Static VAR Compensator (SVC), Static Synchronous Series Compensator (SSSC), STATCOM, and Unified Power Flow Controller (UPFC). Their study demonstrated how these devices enhance power system stability, particularly with respect to rotor-angle stability, frequency stability, and voltage stability. Dudhe [10] reviewed key reactive-power compensation technologies, outlining their operational principles and design characteristics. The study compared shunt and series VAR compensators, noting that shunt compensators reduce active-power losses and offer superior power-factor improvement, while series compensators significantly reduce total reactive-power losses without substantially affecting active-power loss. A case study evaluating both compensation methods was presented to highlight their relative performance. Siregar et al. [11] assessed the performance of a STATCOM integrated into the 150 kV North Sumatra (SUMBAGUT) power system using the Artificial Bee Colony (ABC) optimization algorithm. Simulation results indicated that installing a single STATCOM improved the system voltage profile and reduced active-power losses from 131.40 MW to 121.56 MW. The study emphasized that reactive-power imbalances adversely affect transmission efficiency, influencing the real power delivered to loads and degrading the overall system power factor. The reviewed literature highlights the applications of various FACTS devices and the performance improvements achieved through their deployment. Despite these documented advancements, a significant gap persists in the practical integration of FACTS technologies within Ethiopia's power sector, particularly across the generation, transmission, and distribution segments. This study seeks to address the voltage stability challenges of the selected transmission line using STATCOM and SVC solutions. Although Ethiopia's electric utility has implemented some FACTS technologies—most notably a 900 MVAr SVC installation at the Holeta substation—the broader adoption of SVCs remains limited. Ongoing studies have examined their use in specific parts of the distribution network, including the Kality II substation and railway electrification systems, where SVCs have shown potential for enhancing voltage regulation and improving power quality [12, 13]. Additionally, GIS-based modeling has been applied to evaluate and optimize the 15 kV distribution network in Adama town, where a STATCOM has been recommended for reducing power losses and improving voltage profiles under heavy loading conditions. Current assessments indicate that SVC installations in Ethiopia are restricted to the aforementioned locations, and importantly, neither SVC nor STATCOM devices are presently deployed on the transmission line investigated in this study. This paper will not only contribute to solving the voltage problems on the Debre Berhan to Combolcha II line but will also help the company in comparing the performance of STATCOM and SVC, allowing for a more informed selection of the best device for future applications.

STATCOM generally produces fewer harmonics than SVCs; they still generate switching harmonics that need to be addressed with filtering. SVC can introduce harmonic distortion, particularly at specific frequencies, due to its thyristor-based operation. SVCs are prone to causing resonances within the power system, which can amplify existing harmonics. While STATCOMs generally require less space than SVCs for a given rating, large-scale installations can still be a constraint, especially in urban areas. Designing for harmonic mitigation is crucial for both technologies, requiring careful consideration of the system's characteristics and potential interactions. The higher initial cost of STATCOMs can be a barrier to adoption, especially compared to simpler reactive power compensation solutions. SVCs generally cost around \$100/kVAR. STATCOMs tend to be more expensive, potentially above \$150/kVAR [14-17]. Both are more expensive than capacitor banks but less expensive than synchronous condensers. Costs can vary based on the required rating and specific project requirements. Both technologies involve complex power electronics and control systems, requiring specialized expertise for design, installation, and maintenance. In this paper, only the performance of SVC and STATCOM is compared when the line voltage changes due to the occurrence of a fault or voltage sag, or swell.

2. SVC

A transmission line's resistance and inductance cause a voltage drop when current is flowing through it. As a consequence, the line's receiving end voltage (V_R) is often less than its sending end voltage (V_S). The proportionate change in voltage magnitude at the load bus brought about by a change in load current, such as from no load to full load, is known as voltage regulation.

$$voltage\ regulation = \frac{V_s - V_R}{V_R} \times 100\% \tag{1}$$

$$\Delta\bar{V} = V_S - V_R = Z_s \bar{I} \tag{2}$$

where, Z_S is the feeder impedance and is equal to $R_S + jX_S$. Complex power could be written as

$$\bar{S} = \bar{V}(I)^* = P + jQ \tag{3}$$

$$I = \frac{P - jQ}{V} \tag{4}$$

Substituting I from Eq. (2),

$$\begin{aligned} \Delta\bar{V} = \mathrm{V_S} - \mathrm{V_R} &= \left(R_s + jX_s\right)\left(\frac{P_1 - jQ_1}{V}\right) \\ &= \frac{R_s P_1 + X_s Q_1}{V} + j\frac{X_s P_1 - R_s Q_1}{V} \\ &= \Delta V_R + j\Delta V_x \end{aligned} \tag{5}$$

Thus, the voltage drops across the feeder have two components, one in phase ΔV_R and another in phase quadrature ΔV_X. Generally, in the transmission line, resistance is much less than inductance. So, we could write:

$$\Delta\overline{V} = (X_s)\left(\frac{jP+Q}{V}\right) \tag{6}$$

It is clear from the above discussion that the voltage drop of a transmission line depends on the feeder impedance and the actual reactive power flow. If Q is made zero by injecting the required reactive power using a compensator, then the voltage drop could be written as

$$\Delta\overline{V} = (X_s)\left(\frac{jP}{V}\right) \tag{7}$$

Eq. (7) proves that the voltage drops across the transmission line could be greatly reduced by injecting the required amount of reactive power.

Electrical loads produce reactive power as well as use it. Reactive power balance in a grid fluctuates as well because of the hourly variations in the transmitted load. Unacceptable changes in voltage amplitude, or even a voltage depression or a voltage collapse, may be the outcome. The reactive power needs to manage dynamic voltage oscillations under different system conditions. It can be continually supplied by a quickly acting SVC, which would enhance the transmission and distribution stability of the power system [18]. Installing SVC at one or more suitable points in the network can increase transfer capability and reduce losses while maintaining a smooth voltage profile under different network conditions. SVC installations consist of series-connected anti-parallel Thyristors as shown in Figure 1. Air cored reactors and high voltage capacitor banks are connected in series with the Thyristor valves. This setup is connected to the transmission line through a step-up power transformer. In principle, the SVC consists of Thyristor Switched Capacitors (TSC) and Thyristor Switched or Controlled Reactors (TSR / TCR) [19, 20]. It is a shunt-connected device, and the current is controlled using thyristor valves. It is used in power systems to maintain reactive power. Using inductive and capacitive reactors, SVC can regulate the voltage.

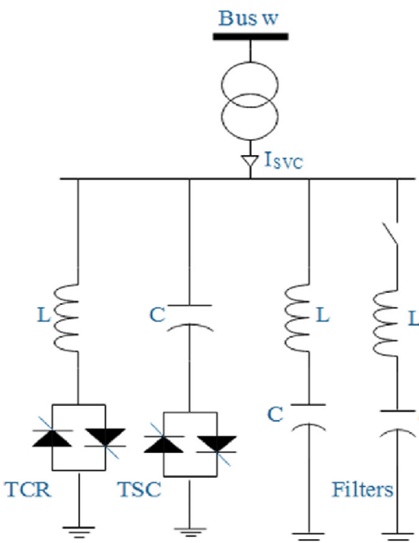

Figure 1. Basic diagram of SVC

Initially, SVC was used for load compensation in steel mills and arc furnaces. In high-power networks, SVCs are used for voltage control and for attaining several other objectives like increasing power transfer in long lines, improving stability with fast-acting voltage regulation, damping low-frequency oscillations due to swing (rotor) modes, and damping sub-synchronous frequency oscillations due to torsional modes.

This paper presents only the performance of the SVC and STATCOM at the time of a voltage sag or swell or the occurrence of a fault. The operation of SVC depends upon the occurrence of a voltage sag or swell. If a voltage sag occurs, then the line is more inductive. SVC needs to supply reactive power by offering equivalent capacitive reactance to the transmission line. Likewise, whenever a fault occurs at the transmission line, the line voltage is decreased. Therefore, the TSC is switched ON, and the TCR is controlled using a PWM technique to supply the required reactive power in order to maintain the line voltage at the rated value.

When TCR is in operation, the equivalent TCR current can be expressed as

$$i(t) = \frac{1}{L}\int Vs(t)dt + constant \tag{8}$$

If we solve Eq. (8) according to the boundary condition $i(\omega t = \alpha) = 0$ and then by Fourier analysis, we get,

$$I1(\alpha) = \frac{V}{\omega L}\left(1 - \frac{2\alpha}{\pi} - \frac{\sin 2\alpha}{\pi}\right) \tag{9}$$

$$I1(\alpha) = V * BTCR(\alpha) \tag{10}$$

$$BTCR(\alpha) = \frac{1}{\omega L}\left(1 - \frac{2\alpha}{\pi} - \frac{\sin 2\alpha}{\pi}\right) \tag{11}$$

If TSC is also switched ON, along with TCR, then,

$$BTSC = XC = C\omega$$

$$BSVC(\alpha) = BTCR(\alpha) + BTSC$$

$$XSVC(\alpha) = 1 / BSVC(\alpha)$$

$$XSVC(\alpha) = \frac{\pi.XL.XC}{XC(2\pi - 2\alpha + \sin 2\alpha) - \pi XL} \tag{12}$$

By adjusting the value of firing angle α, the necessary capacitive reactance XSVC is obtained to supply the reactive power to the transmission line.

Suppose that a voltage swell occurs, then the reactive power only needs to be absorbed by the SVC. At that time, the TSC is in OFF condition, and the TCR current is controlled in order to absorb the required reactive power from the grid in order to maintain the grid voltage constant. The current to be absorbed is determined by the Eq. (11) and in turn it depends upon Eq. (13). By adjusting the value of firing angle α, the necessary capacitive reactance XSVC is obtained to supply the reactive power to the transmission line as given by Eq. (12). The value of BTCR is obtained using Eq. (13). As the TSC is switched OFF and TCR alone in operation,

$$BTCR(\alpha) = BSVC(\alpha) = \frac{1}{\omega L}\left(1 - \frac{2\alpha}{\pi} - \frac{\sin 2\alpha}{\pi}\right) \quad (13)$$

$$XSVC(\alpha) = \frac{1}{BSVC(\alpha)} = \frac{\pi L\omega}{\pi - 2\alpha - \sin 2\alpha} \quad (14)$$

As the value of the firing angle increases, the reactance supplied by the TCR decreases. The reactive power supplied by the TCR also decreases. According to the required amount of reactive absorption, the value of the firing angle is set.

3. STATCOM

The basic topology of STATCOM is shown in Figure 2. STATCOM consists of inductance with internal resistance, VSI, and a DC capacitor [21-24]. Inductance provides the isolation between the inverter circuit and the grid. The required reactive power to be supplied is synthesized from the DC capacitor using an IGBT bridge with an anti-parallel diode.

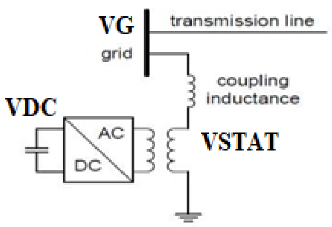

Figure 2. The configuration of STATCOM

From Figure 2, it can be observed that VG is the terminal voltage of the grid, VSTAT is the terminal voltage of STATCOM, XL is the reactance of the coupling inductance, VDC is the terminal DC voltage of the capacitor, and α is the phase angle between the grid and STATCOM terminal voltages.

Active power and reactive power supplied by the STATCOM could be written as

$$P = \frac{VG \times VSTAT}{XL}\sin\alpha \quad (15)$$

$$Q = \frac{VG \times VG}{XL} - \frac{VG \times VSTAT}{XL}\cos\alpha \quad (16)$$

STATCOM is used to control reactive power in phase with system voltage and suppress voltage variation [25-28]. The grid voltage VG is equal to the sum of the STATCOM terminal voltage VSTAT and the voltage drop across the inductance. It means that if the output voltage of STATCOM VSTAT is greater than VG, STATCOM provides reactive power to the system. If VSTAT is smaller than VG, STATCOM absorbs reactive power from the power system. If VSTAT and VG are equal, then STATCOM neither supplies nor absorbs reactive power. By comparing the grid supply voltage with the reference voltage, whether the grid is at a voltage sag or swell is identified. If the grid voltage is not equal to the reference value, then the difference between the grid voltage and the reference voltage is calculated. The corresponding reactive power necessary to maintain the reference value at the grid is calculated. From the reactive power requirement, the terminal voltage of the STATCOM is calculated, and the corresponding PWM pulses are generated by the control circuitry. Applying the PWM technique in the bridge converter, the terminal voltage of STATCOM could be adjusted linearly, and thereby a linear and continuous supply of reactive power is possible. It enhances the stability angle, regulates line voltage, and increases the transmission lines' capability to transmit electricity [29-31].

4. DATA COLLECTION

Primary data for this thesis project came from Ethiopian Electric Power. The information gathered comprises the following: line resistance, line reactance, line length, bus description, bus nominal voltage, transformer data, actual line voltage level, peak, average, and minimum loads of the case study transmission network. In order to operate the data for the program, all relevant information on the high voltage transmission line network in the case study of Ethiopia was gathered from the relevant Ethiopian Electric Power (EEP) offices and examined in this section.

The study area existing EEP transmission network consisting of two high voltage transmission lines. From these, the 132 kV network constitutes one of the lines and the 230 kV network constitutes another line. Both the 230 kV and 132 kV transmission lines are integral components of Ethiopia's national grid, facilitating the distribution of electricity from generation sources to population and industrial centres. The presence of these two high-voltage lines between Debre Berhan and Combolcha highlights the significance of this regional power transmission infrastructure. The 230 kV line between Debre Berhan and Combolcha is part of a project to improve power transmission and trade between Ethiopia and Djibouti. It is stated to have a capacity of 160 MW per circuit.

5. SIMULATION SETUP

The proposed system is simulated in MATLAB Simulink software as shown in Figures 3 and 4. In Figures 3 and 4, instead of the grid, an AC voltage source is used and is connected with the 186 km proposed transmission line from Debre Berhan to Combolcha with the rated load of 160 MW. It's also shown in both figures that both the STATCOM and SVC are connected at the middle of the transmission line as it's a shunt compensation in order to achieve maximum compensation.

The SVC is designed for the reactive power limits of +100 and -100 MVAR, with a nominal voltage and frequency of 230 kV and 50 Hz. An inductor of 1.69 Henry and a capacitor of 6 micro-Farad are used for the SVC.

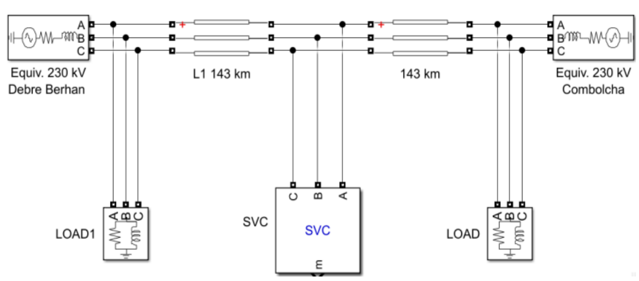

Figure 3. Simulink model of the proposed system using SVC

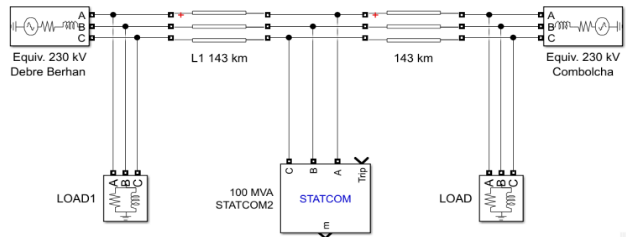

Figure 4. Simulink model of the proposed system using STATCOM

The PI controller is designed for the SVC with the gains of 3 and 300 for the proportional and Integral controllers.

The STATCOM is designed for a power rating of 100 MVAR, with a nominal voltage and frequency of 230 kV and 50 Hz, DC link nominal voltage of 400 kV, and DC link capacitance of 375 microfarads. The PID controller is designed for the STACOM with the gains of 0.3, 10, and 0.22 for the proportional, integral, and differential controllers.

The base voltage is 230 kV, and the base power for both systems is 100 MVA.

6. RESULTS

Figure 5 shows the performance of the STATCOM during a maximum voltage sag condition. The top-most plot indicates the supply voltage with a sag of 25%. The second plot shows the load voltage when the STATCOM is in operation. During a voltage sag, the STATCOM injects a significant amount of reactive power, up to around 0.9 per unit. As a result, in less than 0.07 seconds, the load voltage is maintained much closer to 1 per unit. This demonstrates the ability of the STATCOM to effectively mitigate the voltage sag and maintain a more stable voltage at the load side. The last plot shows the reactive power of 0.9 per unit injected by the STATCOM. The STATCOM reactive power becomes positive, which means it injects reactive power into the system, which helps to stabilize the voltage and maintain the load voltage within acceptable limits. From the results, it could be observed that the rise time is 0.016 seconds, the peak time is 0.0375 seconds with the peak value of 0.972, and the settling time is 0.07 seconds.

Figure 6(a) represents the supply voltage at a magnitude of 1.25 p.u. Figure 6(b) shows the load voltage with the STATCOM in operation. When the overvoltage event occurs, the STATCOM supplies the reactive power, which becomes negative as it absorbs reactive power from the transmission system, maintaining the load voltage within the tolerance of 1.05 p.u. The reactive power absorbed by the STATCOM is 0.8 p.u., as shown in Figure 6(c). From the results, it could be observed that the rise time is 0.025 seconds, the peak time is 0.0175 seconds with the peak value of 1.14, and the settling time is 0.15 seconds.

Figures 7 (a)-(c) and Figures 8(a)-(c) demonstrate the SVC results during the voltage sag and swell conditions, respectively. Figure 8(a) represents the supply voltage dropping to around 0.75 p.u. The load voltage with the SVC in operation, the SVC supplies reactive power to effectively mitigate the voltage drop, maintaining the load voltage at a much higher level of more than 0.95 p.u. The SVC injects a significant amount of reactive power, up to around 1.6 p.u., and maintains the load voltage within an acceptable limit with a rise time of 0.065 seconds, peak time is 0.1 seconds, peak value of 0.95, and the settling time of 0.1 seconds.

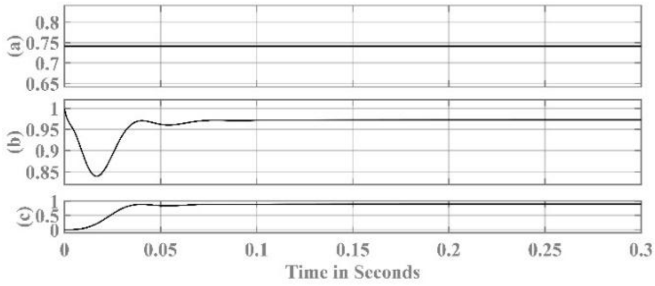

Figure 5. Voltage sag mitigation of STATCOM (a) Supply voltage with a maximum sag of 25% (b) Load voltage maintained by the STATCOM (c) Reactive power injected by the STATCOM

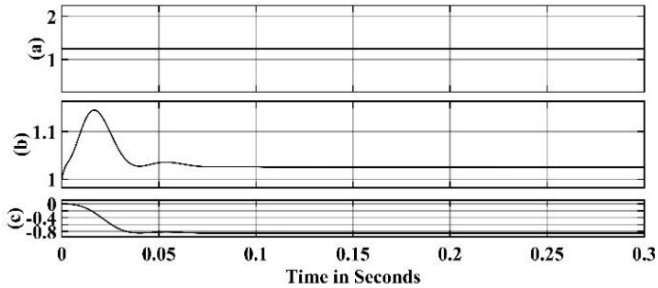

Figure 6. Voltage swell mitigation of STATCOM (a) Supply voltage with a maximum swell of 25% (b) Load voltage maintained by the STATCOM (c) Reactive power injected by the STATCOM

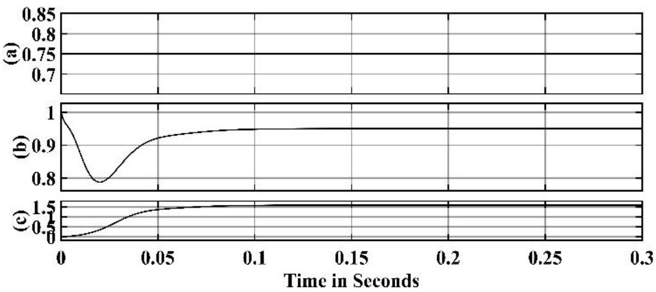

Figure 7. Voltage sag mitigation of SVC (a) Supply voltage with a voltage sag of 25% (b) Load voltage maintained by the SVC (c) Reactive power injected by the SVC

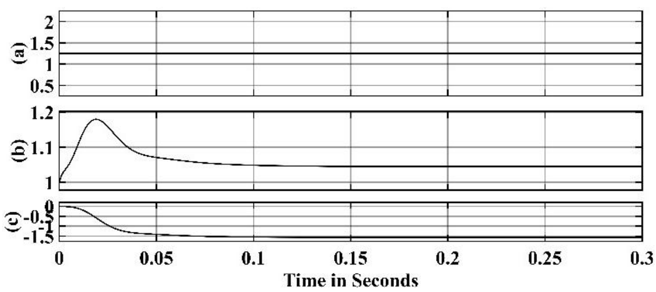

Figure 8. Voltage swell mitigation of SVC (a) Supply voltage with a voltage swell of 25% (b) Load voltage maintained by the SVC (c) Reactive power injected by the SVC

Supply voltage with a maximum voltage swell of 1.25 p.u. is shown in Figure 8. SVC absorbs a significant amount of reactive power, up to around 1.6 p.u., and maintains the load voltage within acceptable limits with a rise time of 0.04 seconds, a peak time is 0.02 seconds with a peak value of 1.18, and a settling time of 0.15 seconds.

The subsequent results illustrate the performance of STATCOM and SVC under fault conditions. Figure 9 illustrates the system response during a three-phase to ground fault through a fault impedance of 25 ohms. The supply voltage, which experiences a dip of 15% between 0.3 and 0.7 seconds, indicates the period of the fault as shown in Figures 9(a)-(c). The load voltage is maintained within the tolerance of 5% by supplying the reactive power of 0.95 p.u. by the STATCOM. It could be observed that the load voltage is compensated within 0.04 seconds by the STATCOM.

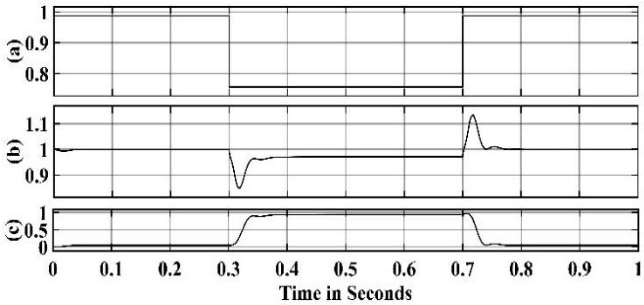

Figure 9. STATCOM response during three-phase to ground fault (a) Supply voltage (b) Load voltage maintained by the STATCOM (c) Reactive power injected by the STATCOM

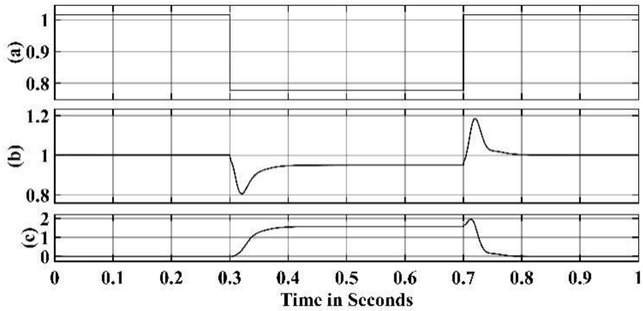

Figure 10. SVC response during three-phase to ground fault (a) Supply voltage (b) Load voltage maintained by the SVC (c) Reactive power injected by the SVC

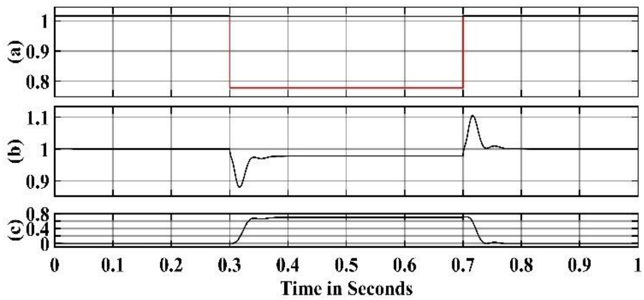

Figure 11. STATCOM response during double line to ground fault (a) Supply voltage (b) Load voltage maintained by the STATCOM (c) Reactive power injected by the STATCOM

Figure 10 illustrates the system's response during a three-phase to ground fault condition when utilizing an SVC. Figures 10(a)-(c) indicate a decline in supply voltage between 0.3 and 0.7 seconds, due to the fault. Figure 10(b) demonstrates that the load voltage is maintained with a tolerance of 0.08 seconds by supplying a reactive power of 1.5 p.u. by the SVC. It could be noted that the reactive power supplied by the STATCOM is only 0.9 p.u., which is much less compared to the SVC.

The effectiveness of STATCOM and SVC when a double line to ground fault occurs in the transmission line is illustrated in Figures 11 and 12, respectively.

It could be observed from the simulation results that when a double line to ground fault occurs, two phase voltages have a voltage sag of 22% and one phase voltage is at its rated value, as shown in Figure 11(a). STATCOM maintains the load voltage at all three phases as shown in Figure 11(b) within 0.04 seconds from the occurrence of a double line to ground fault. The reactive power supplied by the STATCOM is 0.7 p.u as shown in Figure 11(c).

It could be observed from Figure 12 that the SVC can maintain the load voltage during the occurrence of a double-phase-to-ground fault only with the reactive power of 1.23 p.u., with the settling time of 0.1 seconds.

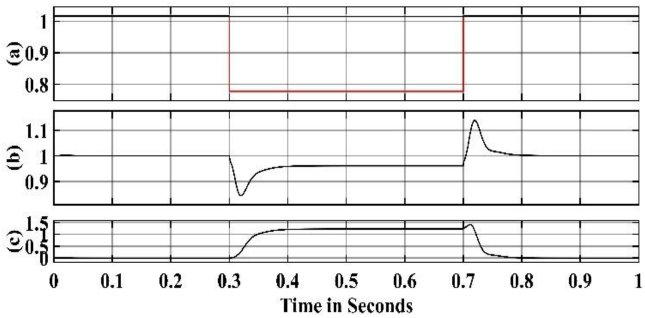

Figure 12. SVC response during double line to ground fault (a) Supply voltage (b) Load voltage maintained by the SVC (c) Reactive power injected by the SVC

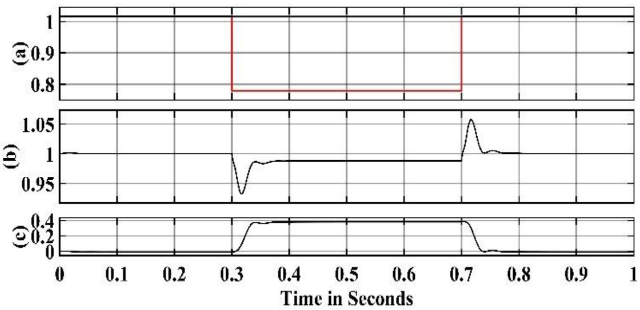

Figure 13. STATCOM response during single line to ground fault (a) Supply voltage (b) Load voltage maintained by the STATCOM (c) Reactive power injected by the STATCOM

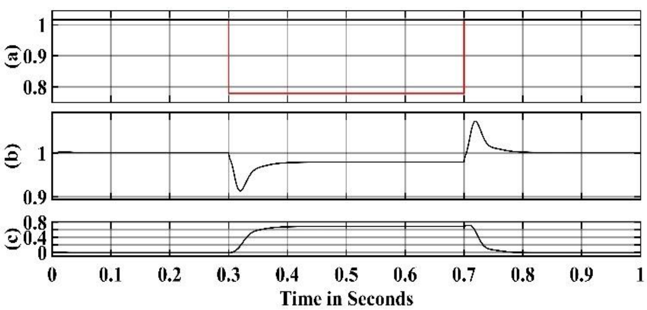

Figure 14. SVC response during single line to ground fault (a) Supply voltage (b) Load voltage maintained by the SVC (c) Reactive power injected by the SVC

Maintenance of load voltage during a single-phase to ground fault through a fault impedance of 25 ohms is shown in Figures 13 and 14 for STATCOM and SVC, respectively. During a single-phase to ground fault, one phase voltage attains a voltage sag of 22%. From Figure 13, it could be observed that the STATCOM mitigates the voltage sag within 0.04 seconds by supplying the reactive power of 0.4 p.u. But the SVC needs 0.08 seconds to maintain the load voltage and needs to supply 0.7 p.u. of reactive power, as shown in Figure 14.

7. DISCUSSION

Performance comparison of both STATCOM and SVC is discussed in this section and is listed in the table for clear understanding. The performance comparison of both STATCOM and SVC when a voltage sag or swell occurs at the transmission line is given in Table 1. From Table 1, it's clear that STATCOM is more effective than SVC with less rise time, less peak time, less peak overshoot, and less reactive power needed compared to SVC in order to maintain the load voltage at the rated value.

The performance comparison during the occurrence of different faults at the transmission line is given in Table 2. From Table 2, it's clear that STATCOM is more effective than SVC with less settling time and less reactive power needed to supply for maintaining the load voltage at rated conditions.

Table 1. Performance under voltage sag and swell

Supply Voltage in p.u.	Rise Time in Milli Seconds		Peak Time in Seconds		Peak over/under Shoot in p.u.		Q in p.u.	
	STATCOM	SVC	STATCOM	SVC	STATCOM	SVC	STATCOM	SVC
0.75	16	65	37	100	0.85	0.79	0.9	1.6
1.25	25	40	17	20	1.14	1.18	-0.9	-1.6

Table 2. Performance during various fault conditions

Type of Fault	Settling Time in Milli Seconds		Q in p.u	
	STATCOM	SVC	STATCOM	SVC
SLG	0.04	0.08	0.4	0.7
LLG	0.04	0.1	0.7	1.23
LLLG	0.04	0.08	0.95	1.5

8. CONCLUSION

In this paper, the basic principles of STATCOM and SVC operations, along with the functions of their components, are explained. The operating characteristics of both FACTS devices are verified through simulation. Both the SVC and STATCOM play crucial roles in reactive power compensation, and they are compared in terms of voltage support. The simulation results demonstrate a clear performance distinction between the STATCOM and SVC in terms of reactive power compensation and voltage regulation. From the results and discussion, it's very clear that the STACOM is faster and more effective than SVC in maintaining the load voltage constant under voltage sag and swell conditions with less rise time, peak time, and less peak overshoot compared to SVC. Moreover, for the same voltage sag or swell compensation, the reactive power supplied is only 0.9 p.u. by the STATCOM, but for the SVC it is 1.6 p.u. During the fault, the STATCOM has cleared the faults within 0.04 seconds, while the SVC has taken 0.08 seconds to clear the same faults. All these results clearly show that the STATCOM outperforms the SVC in all aspects except easy control and lower cost. National Electrification Program (NEP) prioritizes a combination of on-grid and off-grid solutions to achieve this goal. Key areas of focus include strengthening the transmission network, enabling private sector participation in renewable energy generation, and modernizing the grid. Future research directions include optimizing renewable energy integration, improving energy efficiency, and developing smart grids. The government is encouraging private sector investment in renewable energy generation, particularly in non-hydro projects. Research is needed to optimize the integration of variable renewable energy sources (like solar and wind) into the grid while maintaining grid stability and reliability. To maintain the grid stability and reliability, FACTS devices like SVC and STATCOM are currently necessary and need to be studied effectively, as Ethiopia has just started to use these devices.

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