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Modeling and Analysis for the Improvement of High Voltage AC Transmission System Using Static Synchronous Compensator

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Abstract: This paper emphases on improving the performance and stability of high voltage AC transmission system by implementing a Static Synchronous Compensator (STATCOM). The modern electric power system has many challenges due to rising the load demands, long distance transmission and the integration of renewable energy sources. These factors subject to voltage instability, power quality deterioration in high voltage AC transmission network. One of the most effective methods for improving voltage regulation and system stability is the use of static synchronous compensator, STATCOM. In this study, a high voltage transmission system is modeled and analyzed using MATLAB to observe the impact of STATCOM. Simulation results demonstrate significant improvements in voltage stability, power loss and power transfer capacity when the STATCOM is integrated.

Keywords: Static Synchronous Compensator (STATCOM), High Voltage AC Transmission, Reactive Power Compensation, Power Transfer Capacity.

Review Paper

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I. INTRODUCTION

The rapid growth in electrical power demand, combined with the expansion of interconnected power systems, has placed significant pressure on existing transmission networks. Modern power systems often operate near the stability and thermal limits, leading to challenges such as voltage instability, reactive power imbalance, and inefficient power flow management. These problems can result in poor voltage regulation, increased transmission losses and reduced system reliability during dynamics loading conditions or long-distance power transfers.

To overcome these challenges, Flexible AC Transmission Systems (FACTS) have been developed, with the Static Synchronous Compensator (STATCOM) being one of the most widely used devices. An STATCOM can dynamically inject or absorb reactive power, thereby maintain desired voltage levels at various buses in a transmission network.

This paper investigates the modeling and analysis for the improvement of an HVAC transmission system integrated with STATCOM. Using MATLAB/Simulink, the performance of the system is analyzed under maximum load operating conditions. Simulation results are used to evaluate and compare system performance with and without the STATCOM, demonstrating the effectiveness of STATCOM in improving voltage profiles, minimizing power losses, and increasing the overall efficiency of the transmission system. The comparison between uncompensated and compensated systems provides valuable insights into the effectiveness of STATCOM in real-world applications.

II. HIGH VOLTAGE AC TRANSMISSION SYSTEM

High Voltage Alternating Current (HVAC) transmission systems play a vital role in modern power networks. Because of the large power transmitted and the long distances between generation and consumption points, high voltage levels are utilized to decrease current flow, thereby reducing power losses and minimizing voltage drops. The important objectives of an HVAC transmission system are:

i. To deliver electric power with minimum transmission losses,
ii. To maintain voltage levels within acceptable limits throughout the system,
iii. To enhance the power transfer capability while maintaining overall system stability.

HVAC systems are characterized by three key performance aspects, described below:

A. Voltage Regulation

Voltage regulation refers to the ability of a transmission system to maintain the receiving-end voltage within acceptable limits under varying load conditions. When the load increases, the voltage at the receiving end tends to decrease due to the voltage drop across the line impedance. Excessive voltage drops can cause inefficient operation of equipment, deterioration of power quality, and even lead to system instability. The voltage drop at the receiving end should not exceed 5% of the rated voltage.

B. Power Losses

Power losses in HVAC transmission systems primarily occur due to the resistance and reactance of the transmission lines. The most important losses are I^2R losses, which are proportional to the square of the current flowing through the conductors. Moreover, reactive power flow causes additional voltage drops and energy losses along the line. These losses can be minimized by increasing transmission voltage level, enhancing conductor material and implementing reactive power compensation.

C. Power Transfer Capacity

The line capacity is defined as the maximum permissible transfer of electrical power, including both real power (MW) and apparent power (MVA). A transmission line can withstand under normal operating conditions without exceeding its thermal, mechanical, or stability limits. In this research, transmission line capacity such as thermal limit (based on MVA) is used.

III. APPLICATION OF STATCOM FOR TRANSMISSION SYSTEM IMPROVEMENT

STATCOM is applied in power system to stabilize the voltages in weak transmission network, regulate power flow to attain transient stability, reduce transmission losses and increase the power transfer capacity of existing lines. In this paper, there are three main applications of STATCOM are described and analysed.

(i) Voltage Regulation and Stability Improvement:

STATCOM maintains the bus voltage within acceptable limit by dynamically controlling the reactive power exchange with the system. It helps stabilize the voltage profile across the transmission line.

(ii) Loss Reduction:

By improving voltage levels and power factor, STATCOM minimizes both real and reactive power losses in transmission lines.

(iii) Increased Power Transfer Capacity

STATCOM improves the load ability of transmission lines by improving voltage stability and reducing congestion conditions.

IV. MODELING AND SIMULATION FOR 230 kV UPPER MYANMAR TRANSMISSION SYSTEM

This paper implemented modeling and simulation for 230 kV double circuit AC transmission line in Upper Myanmar. The single line diagram of the selected transmission system is shown in Figure 1.

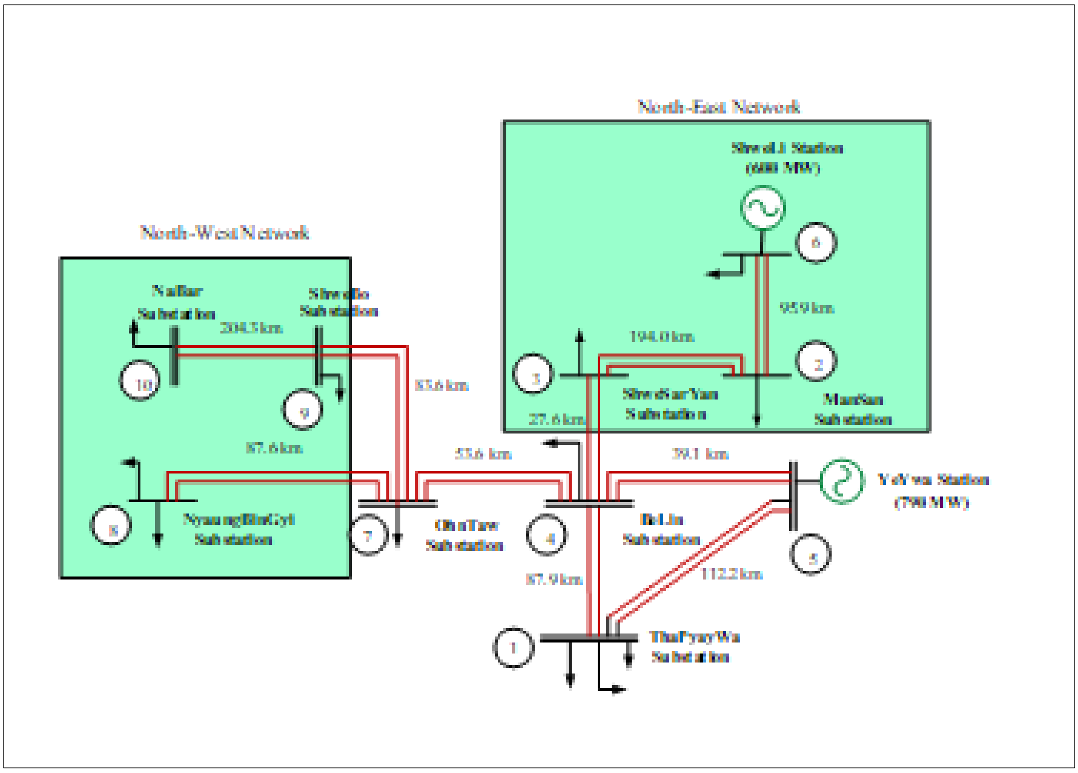

Fig. 1: Single Line Diagram of 230 kV Upper Myanmar Transmission System

Table I: Specification of Double Circuit Transmission Lines

Substation		Voltage Level (kV)	Line Length (km)	I-limit (A)
From	To			
Shweli	Mansan	230	95.9	1425
Mansan	Shwesaryan	230	194.0	975
Shwesaryan	Belin	230	27.6	1770
Yeywa	Belin	230	39.1	1770
Yeywa	Thapyaywa	230	112.2	1593
Thapyaywa	Belin	230	87.9	1682
Belin	Ohntaw	230	53.6	1500
Ohntaw	Nyaungbingyi	230	87.6	1425
Ohntaw	Shwebo	230	83.6	1756
Shwebo	Nabar	230	204.3	1054

In this research, there are two hydro power generation stations are included, Shweli Station (600 MW) and Yeywa Station (790MW). And, the improvement of high voltage AC transmission system is analyzed at ten high voltage double circuit transmission lines. Specification of double circuit transmission lines, voltage level, line length and current limit are described in Table I. The Simulink model is constructed according to single line diagram that is shown in figure and the data described above. The Simulink model for the case study is shown in Figure 2.

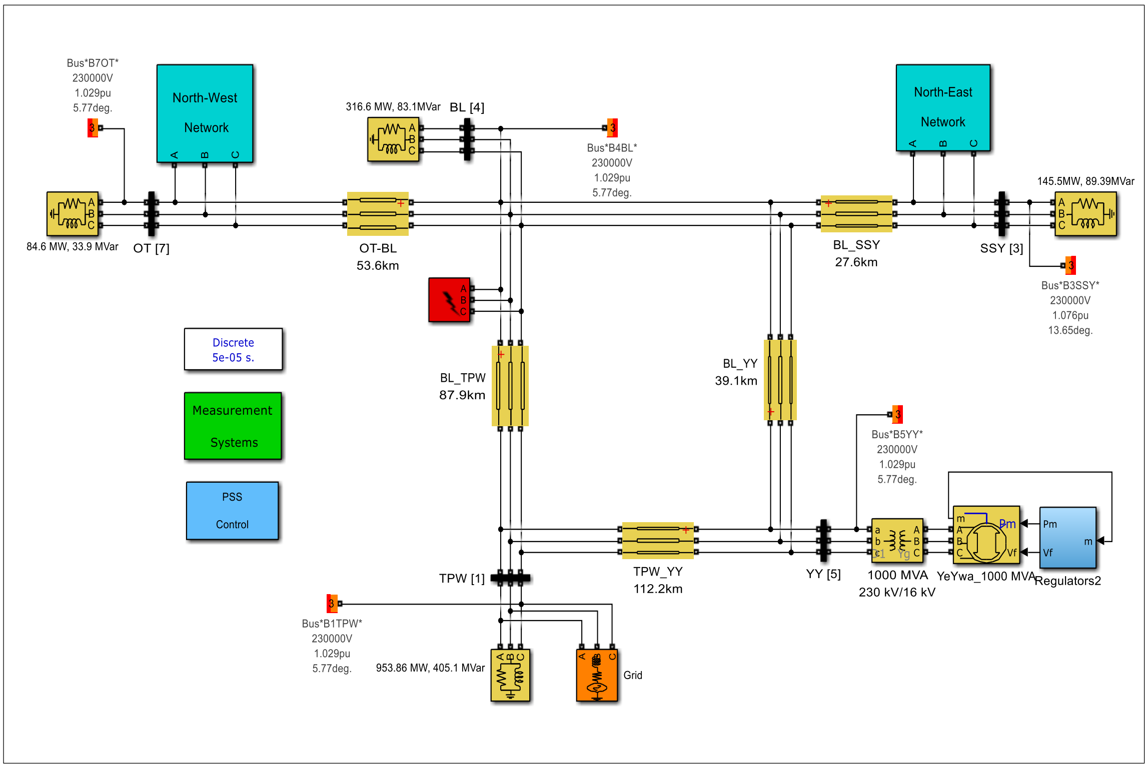

Fig. 2: Simulink Model for the Existing System

To observe the improvement of high voltage AC transmission system, the simulations are carried out for maximum load condition. The load data for the case study is summarized in the Table II, detailing the active and reactive power demands at each bus.

Table II: Loads Data of Case Study (Maximum Condition)

Bus No.	Substation	Active Power (MW)	Reactive Power (MVAr)
1	TPW	953.86	405.1
2	MS	48.1	14.9
3	SSY	145.5	89.39
4	BL	316.6	83.1
5	YY	0	0

Bus No.	Substation	Active Power (MW)	Reactive Power (MVAr)
6	SL	0	0
7	OT	84.6	33.9
8	NBG	236.6	164.8
9	SB	21.19	9.4
10	NB	90.64	25.24

The total load demands of the system are 1897.09 MW and 825.83 MVAr. After modeling of the existing system without STATCOM, the simulations are carried out for normal condition with maximum loads. Figure 3 shows the bus voltages profile at each bus. Among the buses 1, 3, 4, 7, 9 and 10, Bus 8 (Nyaungbingyi substation) has the lowest voltage at 0.8691 p.u, which is below standard acceptable range of 0.95 p.u to1.05 p.u. This indicates a potential issue of voltage instability in that area of the network. In power system, low voltage typically results from inadequate reactive power.

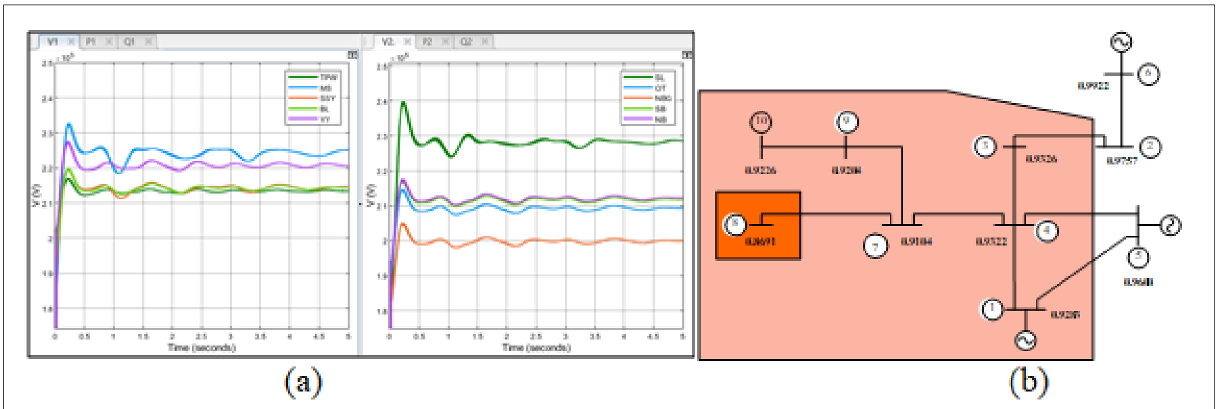

Fig. 3: (a) Simulation Results of Bus Voltage Profile (Without STATCOM) (b) Bus Voltage Condition without STATCOM

As a result, the poor voltage regulation at Bus 8 requires immediate corrective action, and Buses 7,9 and 10 also require voltage support to avoid further voltage deterioration. Long transmission lines and high reactive power demand cause voltage instability, necessitating dynamic compensation.

Figure 4 and Figure 5 show the active and reactive power at each bus without STATCOM. Active and reactive power flow under existing system are described in Figure 6 (a). Active power flows indicate heavy loading on lines like 4-5 (601.8 MW) and 4-7 (444.1 MW), contributing to losses. Unoptimized power flow leads to inefficiencies, especially in lines with high impedance or length. Reactive power shortages are distinct at Bus 8 (164.8 MVAr demand) and Bus 1 (405.1 MVAr), exceeding local generation capacity.

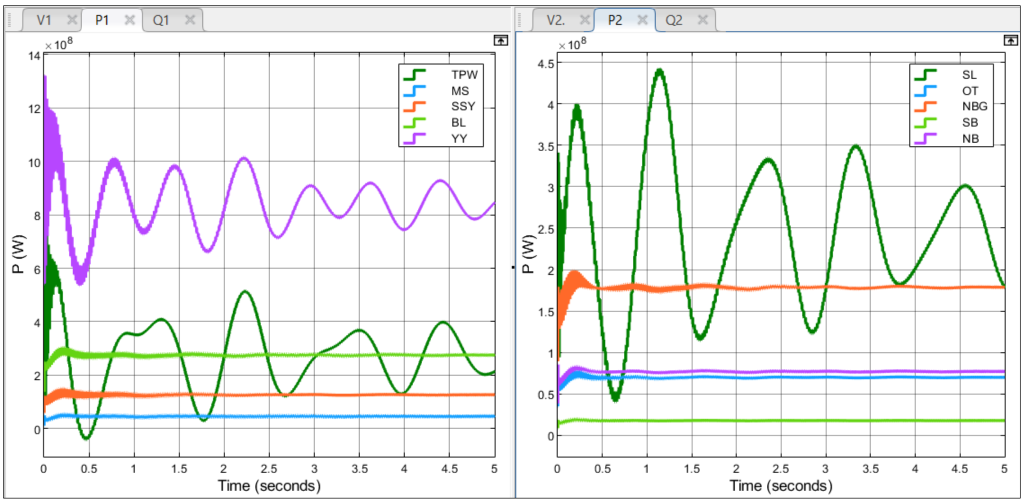

Fig. 4: Simulation Results of Active Power at each Buses (without STATCOM)

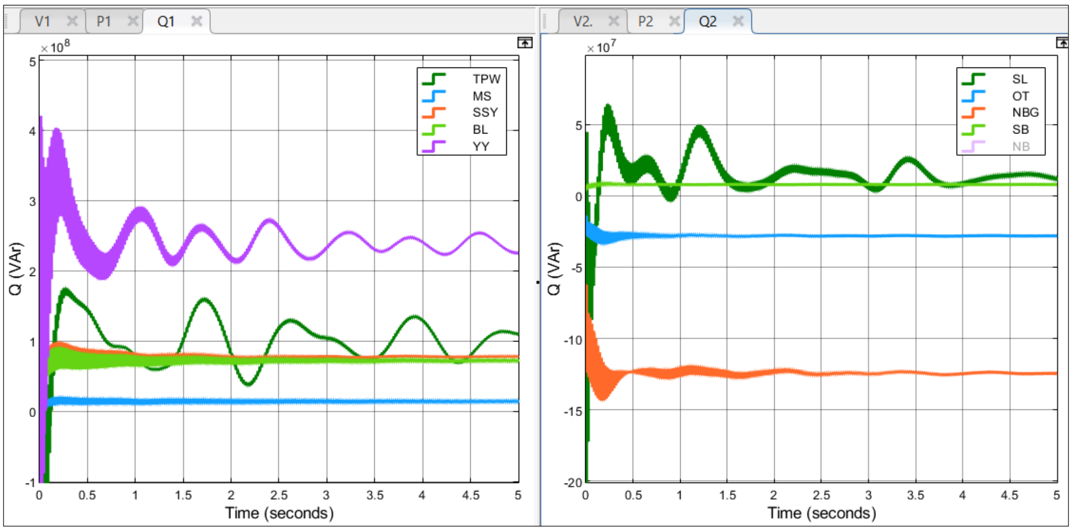

Fig. 5: Simulation Results of Reactive Power at each Buses (without STATCOM)

Reactive power imbalance make worse voltage drops, confirming the need for STATCOM to inject/absorb VARs dynamically. The high reactive power flow on Line 7 to 8 (161.9 MVAr) is associated with low voltages at Bus 7 (0.9104 p.u) and Bus 8 (0.8691 p.u), confirming a reactive power deficiency in this area.

And then, power transfer capacity is carried out from the maximum apparent power and limited apparent power. The resulted power transfer capacity of each transmission line is organized in Figure 6 (b). The Bus 4 to Bus 5 operates at 88.9 % of its thermal limit, making it susceptible to overload under contingency conditions or increased demand. Thus, the Bus 4 to Bus 5 is particularly weak to overload during peak demand or generation shifts.

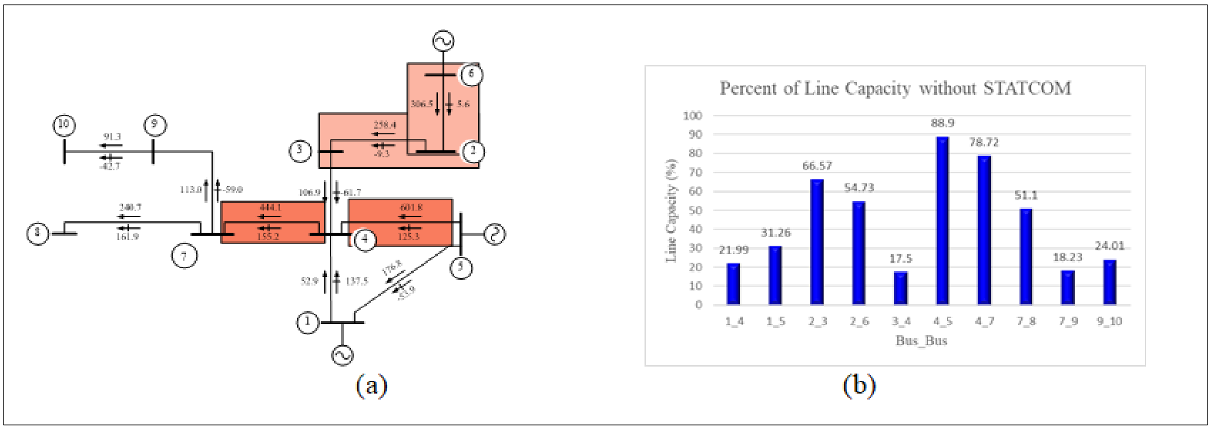

Fig. 6: (a) Active and Reactive Power Flow (without STATCOM) (b) Power Transfer Capacity without STATCOM

Overall, most transmission lines operate within safe margins (<90% of capacity), maintaining system reliability under normal conditions. However, voltage instability remains a concern in the Bus 7, Bus 8 and Bus 9 corridor, primarily driven by excessive reactive power demand.

V. IMPROVEMENT OF SYSTEM USING STATCOM

For the purpose of analysis and simulation, STATCOM is typically modeled as a variable reactive power source connected in shunt to the transmission system.

A. Location and Sizing of STATCOM

In compensation, the most important one is the sizing and allocation of compensation device in the system. To determine the sizing and allocation of STATCOM, the steady state load flow programme is executed with MATLAB. From the simulation results, the location of STATCOM is chosen at Bus 7 (Ohntaw Substation). The required input data to calculate the parameter of STATCOM is shown in Table III.

Table III: Input Data for STATCOM Design

Parameter	Symbol	Rating	Unit
Voltage at STATCOM connection point	V	11	kV
System frequency	f	50	Hz
Active power of load at selected bus	P_{load}	444.1	MW
Reactive power of load at selected bus	Q_{load}	155.2	MVAr
Short circuit level of the bus	S_{sc}	3000	MVA
Resistance to reactance ratio at selected bus	k	0.125	-

Therefore, the following equations (1) to (4) are used to calculate the parameter of STATCOM. Equation (1) is used to calculate the reactive power produced by STATCOM.

$$Q_{STATCOM} = Q_{load} + \frac{P^2_{Load}}{2 \times S_{sc}} + (k\,P_{Load}) \qquad (1)$$

And then, the selection of the DC bus voltage and the DC bus capacitor are calculated by using equation (2) and (3). Next, the selection of an AC inductor is calculated by using equation (4). By inserting the input data into the following equations, the design of STATCOM is calculated. The output data for STATCOM design is tabulated in Table IV.

$$V_{DC} = \frac{2\sqrt{2}\,V_{LL}}{\sqrt{3}\,m} \qquad (2)$$

$$C_{DC} = \frac{I_0}{(2 \times \omega \times D_{DC,pp})} \qquad (3)$$

$$L_{rn} = \frac{m\,V_{DC}}{3\sqrt{3}\,a\,f_s\,I_{cr,pp}} \qquad (4)$$

Table IV: Output Data for STATCOM Design

Parameter	Symbol	Rating	Unit
The Rating of STATCOM	$Q_{STATCOM}$	240	MVAr
The DC Bus Voltage	V_{DC}	20	kV
The DC Bus Capacitor	C_{DC}	87.511	mF
The DC Bus Split Capacitors	C_P, C_M	43.755	mF
The Ripple Filter Inductance	L_{rn}	8.75×10^{-5}	H

B. Modeling and Simulation with STATCOM

The configuration of STATCOM consists of voltage-source converter (VSC), DC capacitor, coupling transformer, converter and power system controls. VSC is the heart of the system, typically a gate turn-off thyristor (GTO-based) converter. In this paper, a three phase, three level neutral-point clamped power converter is used for higher efficiency and power quality. DC capacitor is a large energy storage component on the DC side. It provides a stable DC voltage to the inverter and filters out voltage ripples caused by the switching action of the converter. Coupling transformer is a standard power transformer connecting the output of the converter to the AC grid. It steps up the relatively low AC voltage from the converter to match the higher voltage of the power system. Modeling of STATCOM and the simulink model of transmission line compensated with STATCOM for the improvement of high voltage AC transmission system are shown in Figure 7.

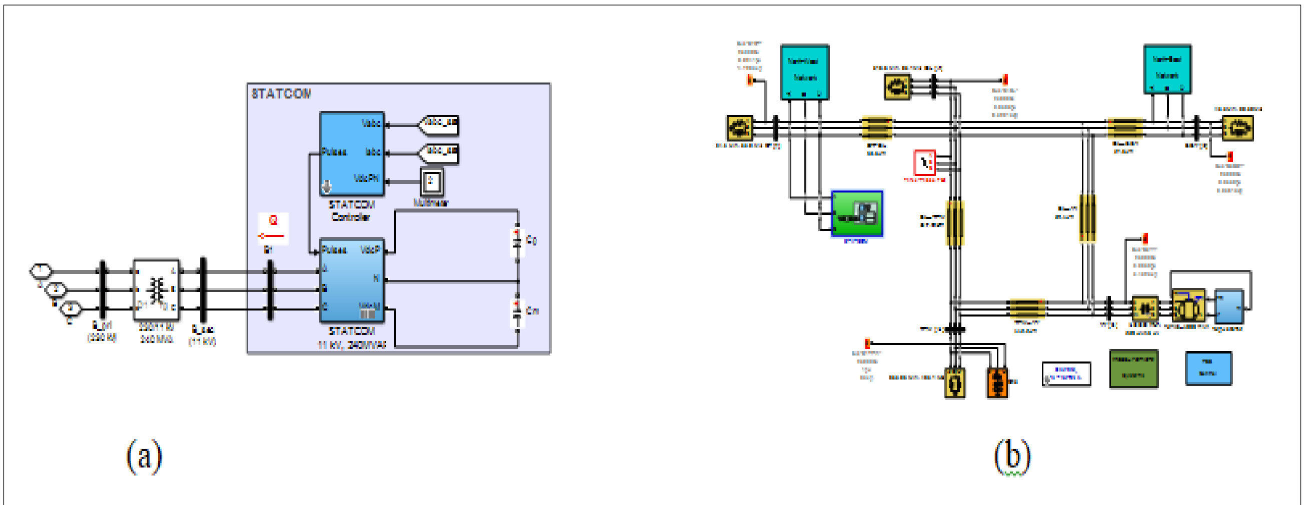

Fig. 7: (a) Modeling for STATCOM (b) Simulink Model of Transmission Line Compensated with STATCOM

Figure 8 shows the bus voltages profile at each bus compensated with STATCOM.

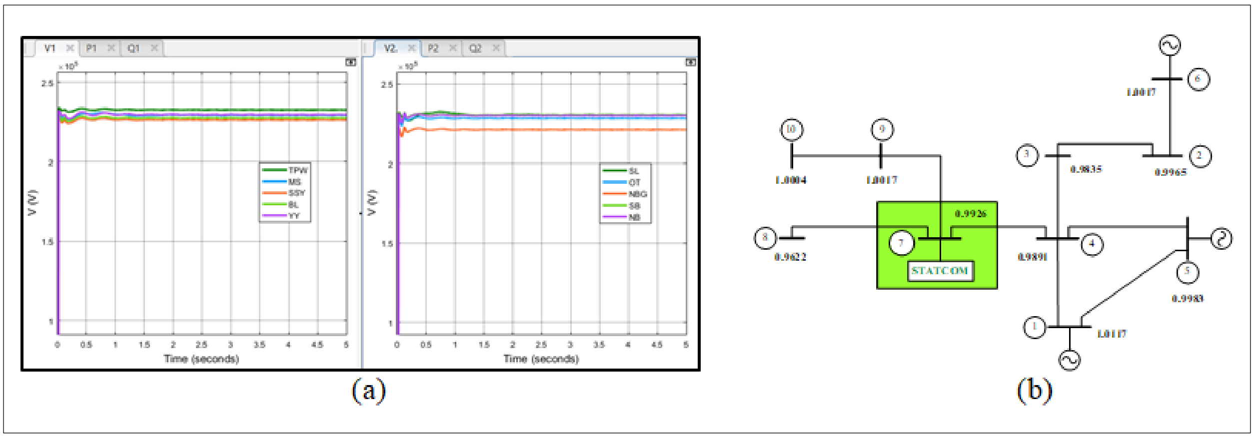

Fig. 8: (a) Simulation Results of Bus Voltage Profile (Compensated with STATCOM) (b) Bus Voltage Condition with STATCOM

Active and reactive power flow in the lines compensated with STATCOM are described in Figure 9.

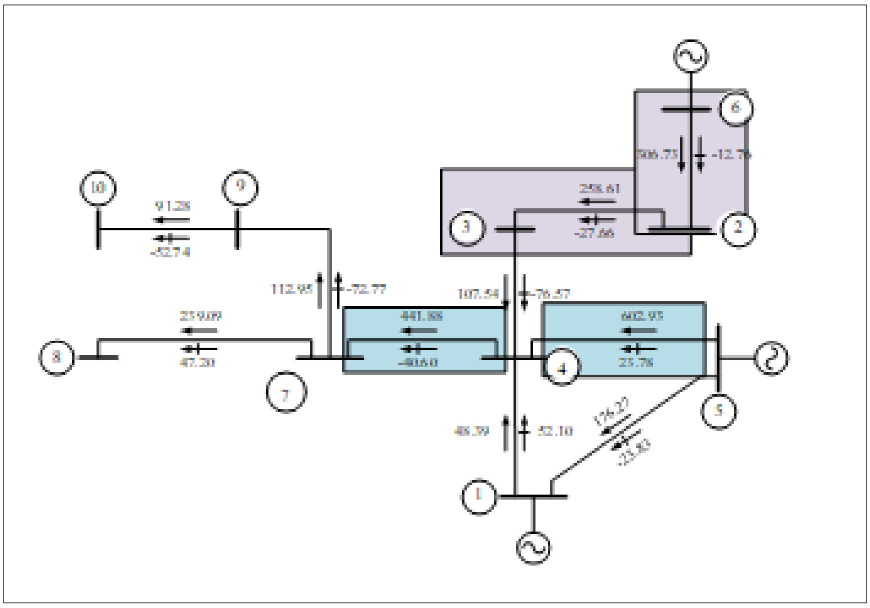

Fig. 9: Line Flow Compensated with STATCOM

VI. ANALYSIS FOR IMPROVEMENT WITH STATCOM

The bus voltage data presented in Table V clearly demonstrates the significant impact of implementing a Static Synchronous Compensator (STATCOM) on system voltage stability. Before compensation, several buses displayed voltage levels well below the nominal operating voltage of 230 kV. For instance, Bus 8 (Nyaungbingyi) recorded the lowest voltage at 199.9 kV, indicating a potentially critical undervoltage condition. After the integration of the STATCOM, Bus 8 voltage increased substantially to 221.3 kV, reflecting the effective injection of reactive power by the STATCOM to stabilize voltage levels. Overall, each of the ten buses experienced a voltage increase with the application of the STATCOM.

Table V: Power System Voltage Profile (Without and with STATCOM)

Bus No.	Bus Voltage without STATCOM (kV)	Bus Voltage with STATCOM (kV)
1.	213.5	232.7
2.	224.4	229.2
3.	214.5	226.2
4.	214.4	227.5
5.	220.8	229.6
6.	228.2	230.4

Bus No.	Bus Voltage without STATCOM (kV)	Bus Voltage with STATCOM (kV)
7.	209.4	228.3
8.	199.9	221.3
9.	211.7	230.4
10.	212.2	230.1

These increases demonstrate the capacity of STATCOM to regulate voltage by supplying or absorbing reactive power as needed. Even buses that were already operating near nominal levels, such as Bus 6 (from 228.2 kV to 230.4 kV), saw improvements. This reflects the STATCOM's role not only in correcting low voltages but also in enhancing voltage uniformity across the system.

Table VI: Power Transfer Capacity (Without and with STATCOM)

Bus-Bus	Line Capacity without STATCOM (%)	Line Capacity with STATCOM (%)	Line Capacity Drop (%)
1-4	21.99	10.61	11.38
1-5	31.26	28.03	3.23
2-3	66.57	66.96	-0.39
2-6	54.73	54.08	0.65
3-4	17.5	18.72	-1.22
4-5	88.9	85.58	3.32
4-7	78.72	74.25	4.47
7-8	51.1	42.93	8.17
7-9	18.23	19.21	-0.98
9-10	24.01	25.11	-1.1

The Table VI presents a comparative analysis of transmission line capacity utilization both without and with the implementation of a STATCOM. The data clearly illustrates that STATCOM integration generally leads to reduced line loading. The most significant reduction is observed on Line1 to 4, where the capacity drops from 21.99% to 10.61%. Line 4 to 5 and 4 to 7, which originally operate at 88.9% and 78.72% capacity respectively, also show improved performance with STATCOM, reducing to 85.58% and 74.25%. These lines are among the most heavily loaded, and the STATCOM helps offload stress and improve system security.

Therefore, the majority of the lines display a positive line capacity drop, indicating a decrease in power flow loading. These results demonstrate the capacity of STATCOM to relieve heavily loaded lines, reduce transmission stress, and enhance overall power flow efficiency. In a few cases, there is a slight increase in line loading. This is likely due to power deflecting effects, where the STATCOM's presence shifts flow paths to more balanced routes. Therefore, STATCOM effectively improves power system stability by reducing line loading on critical transmission paths.

Table VII: Transmission Line Losses and Efficiency (Without and with STATCOM)

Parameter	Without STATCOM	With STATCOM
Total Generation	1932.574 MW	1928.475
Total PQ Load	1897.089 MW	1897.090
Total Losses	35.48 MW	31.385
Efficiency	98.164 %	98.373%
Percent Losses	1.836 %	1.627%

The Table VII illustrates key power system parameters such as generation efficiency and system losses before and after the integration of a STATCOM. One of the most notable improvements is observed in the total transmission losses, which decrease from 35.48 MW to 31.385 MW after the STATCOM is introduced. This 4.095 MW reduction in losses represents improved voltage stability and reduced reactive power circulation. As a result, more generated power reaches the actual load centers. This reduction in losses is also reflected in the percent losses, which drop from 1.836% to 1.627%, confirming that the system becomes more energy-efficient with STATCOM support.

Moreover, overall efficiency improves from 98.164% to 98.373%. This efficiency gain aligns with the STATCOM's role in reactive power compensation, which reduces voltage drops and optimizes real power delivery across the system. It is important to highlight that the total generation decreases slightly from 1932.574 MW to 1928.475 MW. This indicates that the power system is able to meet the same load requirement with reduced generation, due to the efficiency improvements provided by the STATCOM. Thus, the performance is improved by reducing losses and enhancing efficiency by integrating of STATCOM into the system.

VII. CONCLUSION

In conclusion, the integration of the Static Synchronous Compensator into the high-voltage AC transmission network resulted in improved voltage profiles at all observed buses. The system demonstrated significantly improved voltage stability, reduced risks of undervoltage conditions, and enhanced capability to respond to dynamic load variations. These outcomes confirm that the STATCOM is an effective solution for reactive power compensation and voltage regulation in modern power systems. From this research, the STATCOM can operate not only mitigating low voltage conditions but also improving voltage reliability throughout the system.

From the analysis of transmission line capacities without and with STATCOM clearly demonstrates the effectiveness of STATCOM in enhancing power system performance. Most transmission lines showed a decrease in line capacity utilization, verifying the STATCOM's function in reducing congestion, enhancing voltage profiles, and meeting reactive power requirements. This reduction in loading leads to better system stability, reduced transmission losses, and improved voltage regulation. In contrast, a few lines showed a slight increase in capacity usage. However, this is not a disadvantage, since the STATCOM promotes a more balanced flow of electricity across the network.

Overall, the analysis confirms that implementing an STATCOM in a high-voltage AC transmission system improves operational flexibility, eases stress on heavily loaded lines, and increases the reliability and efficiency of power transmission. This supports the STATCOM as a valuable solution for modern power system enhancement and stability improvement.

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