
Improving the Voltage Quality and Power Transfer Capability of Transmission System Using FACTS Controller

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Abstract: One of the main challenges of the future in the utility sector is constructing the new transmission line corridor. This is due to the fact that land compensation cost associated with the expansion of a new transmission line corridor becomes very expensive and also power transmission efficiency is very low. In addition to that, the high carbon emission, which is the major challenge of the world right now, related to the additional conventional energy-based power generation to meet dramatically increased electricity demand and the volatility nature of the existing transmission networks are some of the main drivers to implement FACTS controller in transmission network for flexible, reliable, efficient and stable power transmission. This study accounts modeling of static VAR compensator (SVC), static synchronous compensator (STATCOM), unified power flow controller (UPFC) in a 5-bus transmission system to enhance transmission efficiency and the quality of power supplied to the customer. FACTS devices for improving the transmission line capacity and voltage profile of the power system. The three FACTS controllers are modeled for the standard 5 bus IEEE system based on Newton Raphson algorithm using NEPLAN simulation software in order to investigate their impacts on transmission line capacity and voltage profile improvement. Based on the simulation result, the voltage profile as well as the capacity of the IEEE 5 bus system is improved well by using each of the FACTS controller. From the simulation result we can conclude that the STATCOM and SVC are very efficient in voltage profile improvement whereas the UPFC is well performed for the power transmission capability of the transmission network.

Keywords: FACTS Controller, STATCOM, SVC, Transmission Line Capacity, UPFC, Voltage Profile

1. Introduction

The FACTS controller gave the opportunity to enhance the capacity of the transmission line close to its thermal limit and also increase the controllability of the power system parameters like active and reactive power flow, line current, transmission line impedance, and system operating voltage conventional power system. It has also the capability of improving the stability, power quality and reactive power imbalance of the power system [1-3, 27].

FACTS controllers are categorized as series FACTS controller (SSSC, TCSC), shunt controller (STATCOM, SVC, TCR, TSC), Series-shunt FACTS controller (UPFC, GUPFC) and Series-series FACTS controller (IPFC). Based on their control efficiency, speed of operation and cost, STATCOM, UPFC and SSSC are widely used [1, 27].

The main contribution of the research is implementing NEPLAN to investigate the impact of UPFC, STATCOM and SVC on the voltage quality and power transfer capability improvement of transmission line. FACTS play important role on transmission system like controlling system reliability, improving the security of the system and the efficiency of the power system. It can also provide flexibility on the controllability of power system parameters. But the scope of this study is limited to investigate the impact of UPFC, STATCOM and SVC on the voltage quality and power transfer capability improvement of transmission line.

1.1. Unified Power Flow Compensator

UPFC is a series-shunt power electronics voltage source converter which is emerged as one of the most effective controllers for the control and optimization of power flow and voltage regulation in a complicated AC power system network. It can control three network parameters namely network impedance, current flow and system voltage independently at a time [2]. Its circuit diagram is shown in Figure 1.

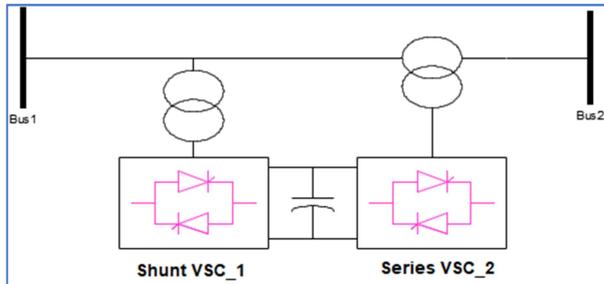


Figure 1. A UPFC Schematic Diagram.

1.2. Static Compensator (STATCOM)

The STATCOM is another effective but relatively cheap voltage sourced converter (VSC) as compared to UPFC and widely installed throughout the world. Figure 2 shows the STATCOM circuit. It is a shunt compensator which is installed at the bus or inserted in parallel to the transmission line through coupling transformer in order to regulate the system voltage by injecting or absorbing reactive power into or from the system which is depend on the system voltage profile. behind a coupling transformer.

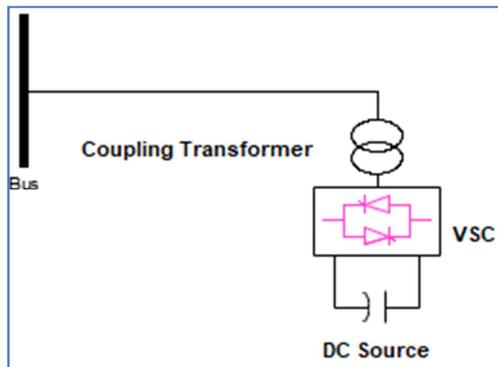


Figure 2. STATCOM Circuit Representation.

The voltage source converter inside the STATCOM can produce a sinusoidal voltage of controllable magnitude and phase angle sourced from capacitor bank or energy storage system (ESS) [3, 10].

The STATCOM can operate both in the inductive and capacitive mode just like the SVC depending on the system voltage. When the system voltage, where the STATCOM is installed, is less than its nominal value, the STATCOM functioned as a capacitor to inject reactive power into the system whereas the STATCOM operates in the inductive mode to absorb extra reactive power from the system when

the system voltage exceeds the nominal value so as to adjust the system voltage value within the standard limit [3, 10]. Figure 3 demonstrates the droop characteristics of the STATCOM at deferent operation region.

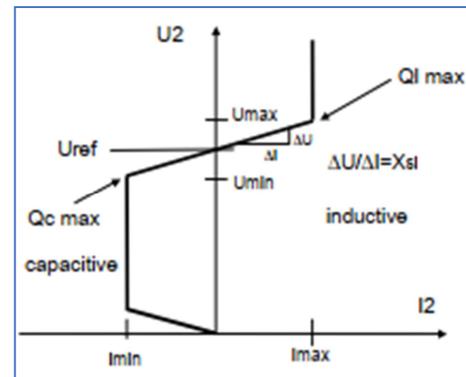


Figure 3. STATCOM V-I Characteristic Curve [3].

1.3. Static VAR Compensator (SVC)

SVC is thyristor controlled first generation FACTS controller shown in Figure 4. It has a very slow switching time and large size as compared to its counterpart, STATCOM.

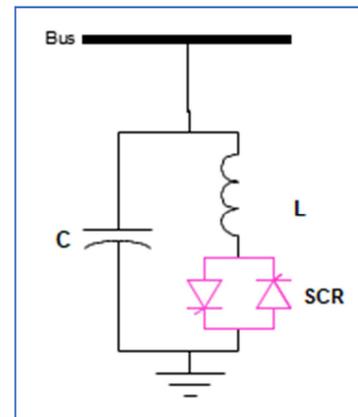


Figure 4. Typical SVC (TSC-TCR) Configuration.

It is functioned as a voltage regulator and power factor corrector for large industrial inductive loads in order to improve stability and power quality of the supply [4]-[9].

2. Steady State Load Flow Study

For a conventional grid, the power flow is from generation to load whereas in a modern grid consists of distributed generation the conventional power flow approach is changed. It can take place from load to generation as a bottom-up approach too [11-14].

The model of the load flow both in conventional and smart grid is done using Newton Raphson (NR) algorithm. This model is the most efficient model for both conventional and smart grid with and without the incorporation of FACTS controller. It is because of fast convergence property and a very small memory requirement [25, 28].

Now the actual Newton Raphson load flow model with UPFC is modified as [16-20].

$$\begin{bmatrix} \Delta P \\ \Delta Q \\ \Delta P_{se} \\ \Delta V_B \\ \Delta P_L \\ \Delta Q_L \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} & \frac{\partial P}{\partial \theta_{se}} & \frac{\partial P}{\partial V_{se}} & \frac{\partial P}{\partial \theta_{sh}} & \frac{\partial P}{\partial V_{sh}} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} & \frac{\partial Q}{\partial \theta_{se}} & \frac{\partial Q}{\partial V_{se}} & \frac{\partial Q}{\partial \theta_{sh}} & \frac{\partial Q}{\partial V_{sh}} \\ \frac{\partial P_{se}}{\partial \theta} & \frac{\partial P_{se}}{\partial V} & \frac{\partial P_{se}}{\partial \theta_{se}} & \frac{\partial P_{se}}{\partial V_{se}} & \frac{\partial P_{se}}{\partial \theta_{sh}} & \frac{\partial P_{se}}{\partial V_{sh}} \\ \frac{\partial V_B}{\partial \theta} & \frac{\partial V_B}{\partial V} & \frac{\partial V_B}{\partial \theta_{se}} & \frac{\partial V_B}{\partial V_{se}} & \frac{\partial V_B}{\partial \theta_{sh}} & \frac{\partial V_B}{\partial V_{sh}} \\ \frac{\partial P_L}{\partial \theta} & \frac{\partial P_L}{\partial V} & \frac{\partial P_L}{\partial \theta_{se}} & \frac{\partial P_L}{\partial V_{se}} & \frac{\partial P_L}{\partial \theta_{sh}} & \frac{\partial P_L}{\partial V_{sh}} \\ \frac{\partial Q_L}{\partial \theta} & \frac{\partial Q_L}{\partial V} & \frac{\partial Q_L}{\partial \theta_{se}} & \frac{\partial Q_L}{\partial V_{se}} & \frac{\partial Q_L}{\partial \theta_{sh}} & \frac{\partial Q_L}{\partial V_{sh}} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \\ \Delta \theta_{se} \\ \Delta V_{se} \\ \Delta \theta_{sh} \\ \Delta V_{sh} \end{bmatrix} \quad (17)$$

3.2. STATCOM Power Flow Model

The STATCOM is modelled using its shunt coupling transformer (Zsh) and voltage source converter (Vsh) as shown in Figure 6. These new terms increase the complexity of the NR load flow model of STATCOM [24, 26].

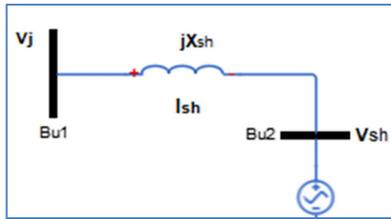


Figure 6. The STATCOM Model.

The current and the power injected at bus j incorporating STATCOM at sending end terminal of bus j is computed using the following Equations [26].

$$I_j = \sum_{k=1}^n V_k Y_{jk} + I_{sh} \quad (18)$$

$$I_{sh} = y_{sh}(V_j - V_{sh})$$

$$P_j = \sum_{k=1}^n V_j V_k Y_{jk} \cos(\theta_j - \theta_k - \phi_{jk}) - V_j V_{sh} y_{sh} \cos(\theta_j - \theta_{sh} - \phi_{ysh}) \quad (19)$$

$$Q_j = \sum_{k=1}^n V_j V_k Y_{jk} \sin(\theta_j - \theta_k - \phi_{jk}) - V_j V_{sh} y_{sh} \sin(\theta_j - \theta_{sh} - \phi_{ysh}) \quad (20)$$

The real power delivered by the STATCOM connected at bus j is:

$$P_{STATCOM} = P_{sh} = \text{Re}[V_{sh}(-I_{sh}^*)] \\ P_{sh} = V_{sh}^2 y_{sh} \cos(\phi_{ysh}) - V_j V_{sh} y_{sh} \cos(\theta_{sh} - \theta_i - \phi_{ysh}) \quad (21)$$

The NR load flow model of an n-bus system containing STATCOM is expressed using equation (22) [24, 26].

$$\begin{bmatrix} \Delta P \\ \Delta Q \\ \Delta P_{sh} \\ \Delta V_{bus} \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} & \frac{\partial P}{\partial \theta_{sh}} & \frac{\partial P}{\partial V_{sh}} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} & \frac{\partial Q}{\partial \theta_{sh}} & \frac{\partial Q}{\partial V_{sh}} \\ \frac{\partial P_{sh}}{\partial \theta} & \frac{\partial P_{sh}}{\partial V} & \frac{\partial P_{sh}}{\partial \theta_{sh}} & \frac{\partial P_{sh}}{\partial V_{sh}} \\ \frac{\partial V_{bus}}{\partial \theta} & \frac{\partial V_{bus}}{\partial V} & \frac{\partial V_{bus}}{\partial \theta_{sh}} & \frac{\partial V_{bus}}{\partial V_{sh}} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \\ \Delta \theta_{sh} \\ \Delta V_{sh} \end{bmatrix} \quad (22)$$

3.3. Implemented System

The 5 bus IEEE power system implemented using the most power full power system software tool; NEPLAN was used for system simulation.

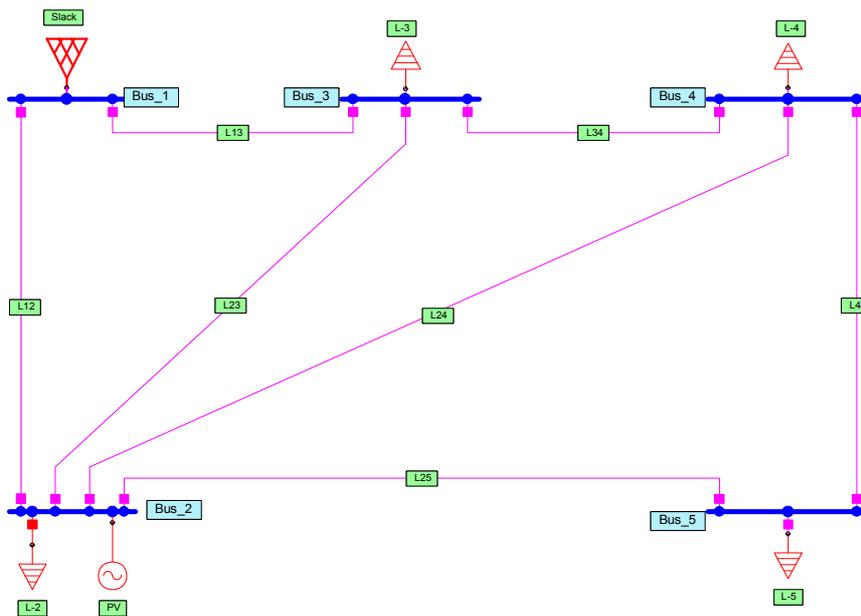


Figure 7. The 5 bus IEEE system drawn using NEPLAN.

The 5 bus IEEE system single line diagram is shown in Figure 7. 100 MVA and 100 KV base values are considered to simulate the system. The load, bus, line and generator data of the 5 bus IEEE system were presented in Tables 1 and 2.

Table 1. Bus, load and generator data.

Bus	Bus type	V [pu]	Phase [deg.]	Pgi [pu]	Qgi [pu]	Pdi [pu]	Qdi [pu]
1	slack	1.06	0	0.0	0.0	0.0	0.0
2	PV	1	0	0.4	0.0	0.2	0.1
3	PQ	1	0	0.0	0.0	0.45	0.15
4	PQ	1	0	0.0	0.0	0.4	0.05
5	PQ	1	0	0.0	0.0	0.6	0.10

Table 2. Transmission line data.

From Bus	To Bus	R [pu]	X [pu]	B [pu]
1	2	0.02	0.06	0.06
1	3	0.08	0.24	0.05
2	3	0.06	0.18	0.04
2	4	0.06	0.18	0.04
2	5	0.04	0.12	0.03
3	4	0.01	0.03	0.02
4	5	0.08	0.24	0.05

3.4. Justification of FACTS Location

The location of SVC, STATCOM, and UPFC is selected based on the bus and branch ID that have higher voltage quality issue and higher real power loss phenomena under steady state Newton Raphson load flow analysis as presented in section 4 of Table 3 and Table 4.

4. Simulation Result

4.1. Simulation Result without FACTS

The simulation result of the 5 bus IEEE power system based on newton Raphson (NR) load flow models were presented in Tables 3 and 4.

Table 3. Voltage output of the system without FACTS.

Bus	V2 [p.u.]	phase [deg.]	P gen [p.u.]	Q gen [p.u.]	P load [p.u.]	Q load [p.u.]
Bus1	1.060	0.00	1.3112	0.9082	0.00	0.00
Bus2	1.000	-2.06	0.4000	-0.616	0.20	0.10
Bus3	0.987	-4.64	0.0000	0.0000	0.45	0.15
Bus4	0.984	-4.96	0.0000	0.0000	0.40	0.05
Bus5	0.972	-5.76	0.0000	0.0000	0.60	0.10

Table 4. Line flow of an IEEE 5 bus system.

From Bus	To Bus	Line	P Flow [p.u.]	Q Flow [p.u.]	P Loss [p.u.]	Q Loss [p.u.]
Bus1	Bus3	1	0.4179	0.1682	0.0152	-0.0069
Bus3	Bus4	2	0.1939	0.0286	0.0004	-0.0182
Bus2	Bus5	3	0.5466	0.0556	0.0122	0.0073
Bus2	Bus3	4	0.2447	-0.0252	0.0036	-0.0287
Bus2	Bus4	5	0.2771	-0.0172	0.0046	-0.0255
Bus1	Bus2	6	0.8933	0.7400	0.0249	0.0109
Bus4	Bus5	7	0.0660	0.0052	0.0004	-0.0465

4.2. Simulation Result with STATCOM

The STATCOM is placed at bus 3 shown in Figure 8 to improve the voltage. From the simulation result, the STATCOM injects 20.47 MVAR reactive power to the network at bus 3 to push the voltage of it from 0.987pu to 1.

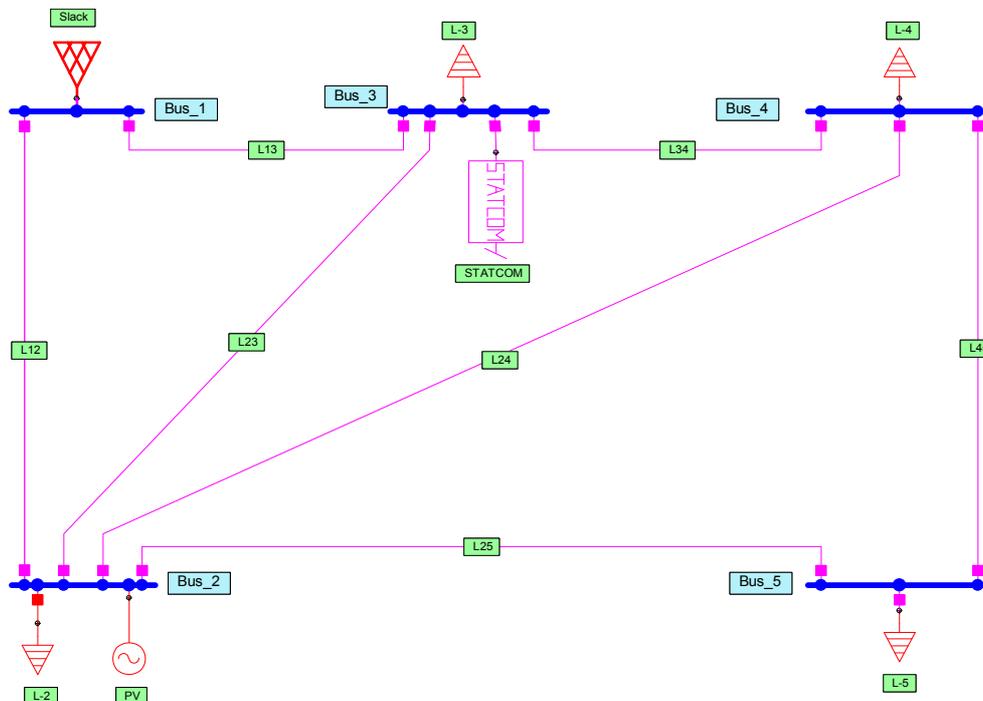


Figure 8. The IEEE-5 bus system drawn with STATCOM.

Table 5. Voltage output of the system with STATCOM.

Bus	V	phase	P gen	Q gen	P load	Q load
	[p.u.]	[deg]	[p.u.]	[p.u.]	[p.u.]	[p.u.]
Bus1	1.060	0.00	1.31	0.85	0.00	0.00
Bus2	1.000	-2.05	0.40	-0.77	0.20	0.10
Bus3	1.000	-4.84	0.00	0.20	0.45	0.15
Bus4	0.994	-5.11	0.00	0.00	0.40	0.05
Bus5	0.975	-5.80	0.00	0.00	0.60	0.10

Table 6. Line flow result of the system with STATCOM.

From Bus	To Bus	Line	P Flow	Q Flow	P Loss	Q Loss
			[p.u.]	[p.u.]	[p.u.]	[p.u.]
Bus1	Bus3	1	0.4195	0.1128	0.0139	-0.0113
Bus3	Bus4	2	0.1965	0.1119	0.0005	-0.0183
Bus2	Bus5	3	0.5448	0.0275	0.0119	0.0066
Bus2	Bus3	4	0.2449	-0.0951	0.0039	-0.0282
Bus2	Bus4	5	0.2766	-0.0732	0.0048	-0.0255
Bus1	Bus2	6	0.8911	0.7406	0.0248	0.0107
Bus4	Bus5	7	0.0678	0.0325	0.0006	-0.0466

As we see from the result of load flow analysis the result in Tables 5 & 6, STATCOM have little impact on transmission line capacity improvement rather it can effectively control the voltage at the bus bar

As we see from the result of load flow analysis the result in Tables 5 & 6, STATCOM have little impact on transmission line

4.3. Simulation Result with UPFC

The system is simulated when UPFC is placed at the sending side of bus 3 as shown in Figure 9 through the line L23. It compensates the series impedance of the line and independently controls the voltage at the buses also. The simulation result dictates the UPFC boosts the capacity of the transmission line L23 good enough.

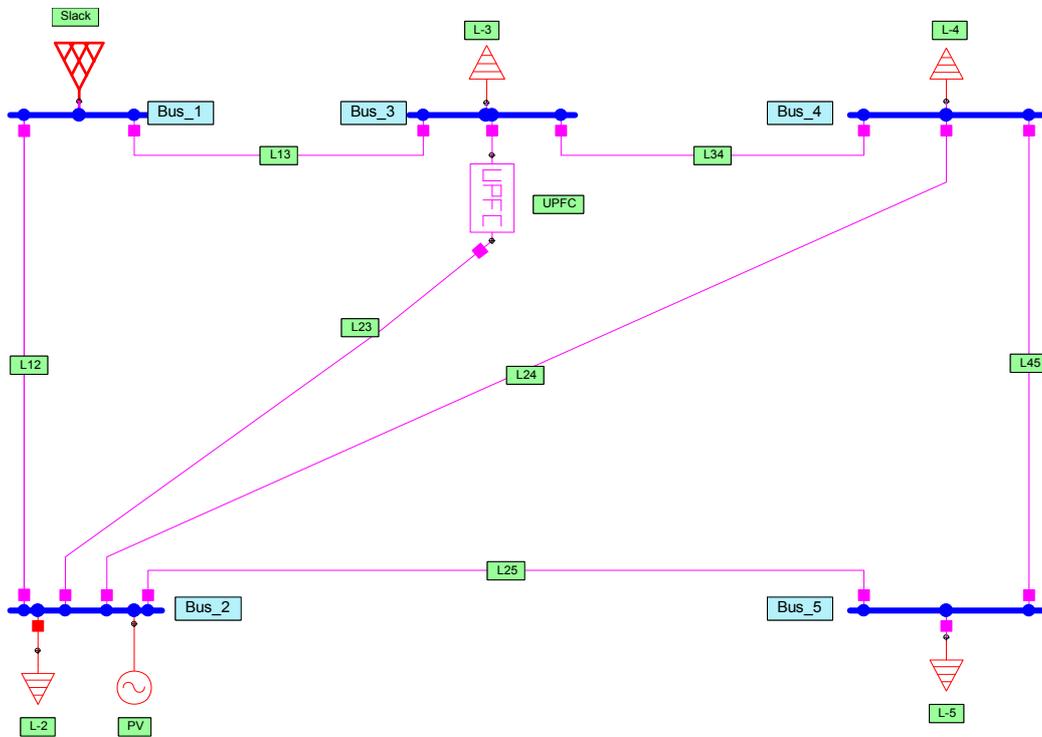


Figure 9. The 5 bus IEEE system simulated under UPFC.

Table 7. Voltage output of the system under UPFC.

Bus	V	phase	P gen	Q gen	P load	Q load
	[p.u.]	[deg]	[p.u.]	[p.u.]	[p.u.]	[p.u.]
Bus1	1.06	0.00	1.30	0.85	0.00	0.00
Bus2	1.00	-2.52	0.40	-0.56	0.20	0.10
Bus3	1.00	-2.84	0.00	0.00	0.45	0.15
Bus4	0.99	-3.60	0.00	0.00	0.40	0.05
Bus5	0.98	-5.60	0.00	0.00	0.60	0.10

From the simulation result, the UPFC produced 20.63 MVAR of power in order to keep the voltage value 1 p.u at bus 3 and the active power loss 0 MW at branch L23. The UPFC also enhances the overall network capacity by 1.2MW.

The results in Table 7 & Table 8 show, UPFC could improve the voltage profile and the power transferable capacity of the transmission line.

Table 8. Line flow result of the system with UPFC.

From Bus	To Bus	Line	P Flow	Q Flow	P Loss	Q Loss
			[p.u.]	[p.u.]	[p.u.]	[p.u.]
Bus1	Bus3	1	0.278	0.150	0.008	-0.030
Bus3	Bus4	2	0.451	0.027	0.002	-0.014
Bus2	Bus5	3	0.459	0.048	0.009	-0.004
Bus2	Bus3	4	0.630	0.001	0.000	0.004
Bus2	Bus4	5	0.103	-0.023	0.001	-0.038
Bus1	Bus2	6	1.021	0.703	0.028	0.021
Bus4	Bus5	7	0.152	0.006	0.002	-0.043

4.4. Simulation Result with SVC

The static var compensator is placed at bus-3 of the IEEE system in order to examine the power transfer capability and voltage control capability of the SVC. The power system with SVC controller was shown in Figure 10 demonstrates

the SVC placement in the IEEE 5 bus system drawn using NEPLAN in order to simulate its performance. Reactive power rating of the SVC was $\pm 100MVA$, and the gradient of the SVC characteristic curve is $X_{sl} = 25\%$. The voltage profile and the line flow obtained after simulating the system was shown in Tables 9 & 10.

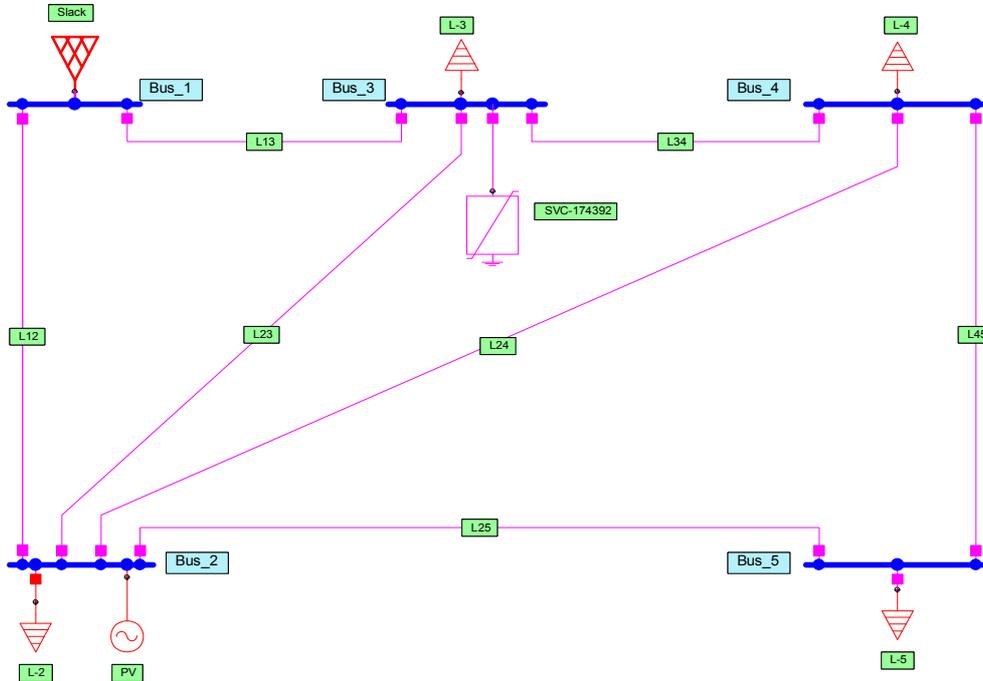


Figure 10. IEEE-5 bus power system simulated with SVC.

The NR load flow solution of the system shows that the SVC generates 20.47MVAR reactive power and operates in the inductive region to keep the voltage at bus 3, 1pu.

Table 9. Voltage output of the system with SVC.

Bus	V [p.u.]	phase [deg]	P gen [p.u.]	Q gen [p.u.]	P load [p.u.]	Q load [p.u.]
Bus1	1.060	0.00	0.131	0.853	0.000	0.000
Bus2	1.000	-2.10	0.400	0.000	0.200	0.871
Bus3	1.000	-4.80	0.000	0.000	0.450	0.150
Bus4	0.994	-5.10	0.000	0.000	0.400	0.050
Bus5	0.975	-5.80	0.000	0.000	0.600	0.100

Table 10. Line flow result of the System with SVC.

From Bus	To Bus	Line	P Flow [p.u.]	Q Flow [p.u.]	P Loss [p.u.]	Q Loss [p.u.]
Bus1	Bus3	1	0.420	0.113	0.014	-0.011
Bus3	Bus4	2	0.197	0.112	0.001	-0.012
Bus2	Bus5	3	0.545	0.028	0.012	0.007
Bus2	Bus3	4	0.245	-0.109	0.004	-0.028
Bus2	Bus4	5	0.277	-0.073	0.005	-0.026
Bus1	Bus2	6	0.891	0.741	0.025	0.011
Bus4	Bus5	7	0.068	0.033	0.001	-0.047

5. Result Comparison

The simulation results were presented here one with respect to the other FACTS technology to asses which technology is more effective in voltage control and which one is also more attractive in line capacity improvement.

As we seen from Figure 11. SVC, UPFC and STATCOM are good voltage controller regardless of their speed of response for dynamic nature of voltage profile variation.

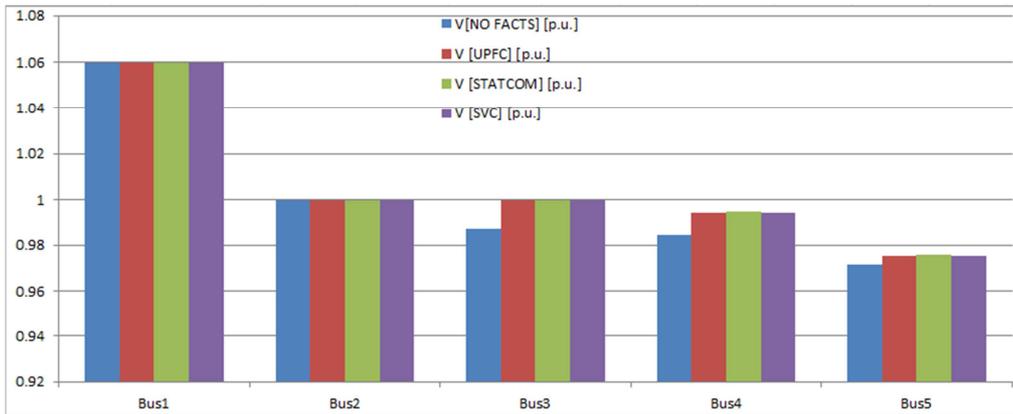


Figure 11. The Voltage output simulation result comparison of the 5 bus IEEE system using SVC, UPFC and STATCOM.

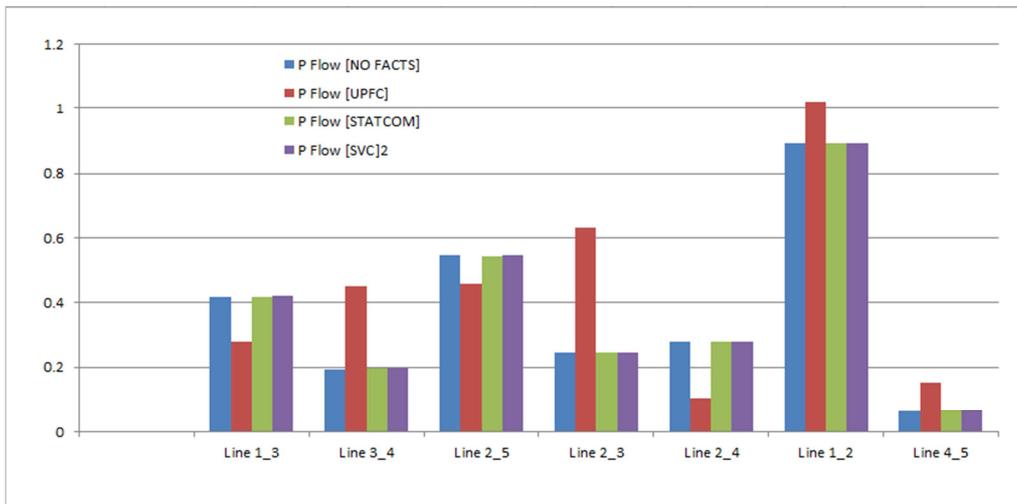


Figure 12. The line flow simulation result comparison of a 5-bus IEEE system using SVC, UPFC and STATCOM.

As we observed from Figures 12 & 13, the UPFC controller enhances the line capacity connected with that element but the transmission line parameter is a big matter during compensation. The transmission network power loss is also greatly reduced.

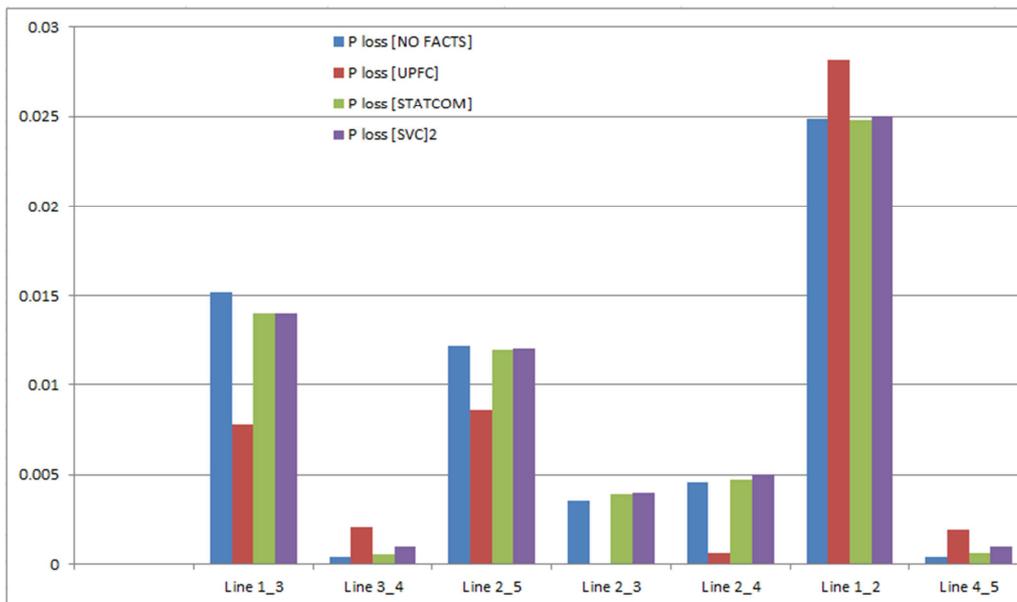


Figure 13. The line loss simulation result comparison of IEEE 5 bus system using SVC, UPFC and STATCOM.

6. Data Availability

The IEEE 5 bus data is presented in Tables 1 & 2 but raw/processed data required to reproduce these findings cannot be shared at this time as the data also form part of an ongoing study.

7. Summary

As seen from the simulation result, UPFC is the best line capacity enhancer and loss absorber, whereas STATCOM and SVC are a better voltage regulator FACTS controller. Overall, the simulation result shows, FACTS controllers are capable of improving the capacity of the transmission line, the controllability of power system parameters, reducing power system network power loss and effectively controlling the system voltage magnitude and phase angle.

Acronyms

AC /Alternating Current/
 ESS /Energy Storage System/
 FACTS /Flexible AC Transmission System/
 GUPFC /Generalized Power Flow Controller/
 ID /Identification/
 IEEE /Institute of Electrical and Electronics Engineers/
 IPFC /Inter-line Power Flow Controller/
 NR /Newton Raphson/
 SSSC /Static Synchronous Series Compensator/
 STATCOM /Static Compensator/
 SVC /Static VAR Compensator/
 TCR /Thyristor Controlled Reactor/
 TCSC /Thyristor Controlled Series Compensator/
 TSC /Thyristor Switched Capacitor/
 UPFC /Unified Power Flow Controller/
 VSC /Voltage Source Converter/

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