Modelling, Simulation And Comparison Of Various FACTS Devices In Power System

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Abstract

Modelling and simulation of Fixed Capacitor Thyristor Controlled Reactor (FC-TCR), Static synchronous compensator (STATCOM), Thyristor controlled Series Capacitor (TCSC), Static synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) for power system stability enhancement and improvement of power transfer capability have been presented in this paper. First, power flow results are obtained and then power (real and reactive power) profiles have been studied for an uncompensated system and then compared with the results obtained after compensating the system using the above-mentioned FACTS devices. The simulation results demonstrate the performance of the system for each of the FACTS devices in improving the power profile and thereby voltage stability of the same. All simulations have been carried out in MATLAB/SIMULINK environment.

Keywords- *FACTS, real and reactive power, FC-TCR, STATCOM, Voltage stability, SSSC, TCSC, power profile, UPFC.*

1. Introduction

Modern power system is complex and it is essential to fulfil the demand with better power quality. Advanced technologies are nowadays being used for improving power system reliability, security and profitability and due to this power quality is improved. Voltage stability, voltage security and power profile improvement are essential for power quality improvement. To achieve optimum performance of power system it is required to control reactive power flow in the network. Construction of new transmission lines and power stations increase the problem of system operation as well as the overall cost. Regulatory limitation on the expansion of system network has resulted in reduction in stability margin thereby increasing the risk of voltage collapse [3]. Voltage collapse occurs in power system when system is faulted, heavily loaded and there is a sudden increase in the demand of reactive power. Voltage instability in power system occurs when the system is unable to meet the reactive power demand.

Reactive power imbalance occur when system is faulted, heavily loaded and voltage fluctuation is there. Reactive power balance can be regained by connecting a device with the transmission line which can inject or absorb reactive power based on system requirement [4].One of the most important reactive power sources is FACTS (Flexible A.C transmission system) device. FACTS may be defined as a power

electronic based semiconductor device which can inject or absorb reactive power in a system as per requirement. This device allows “Flexible” operation of an AC system without stressing the system. In this paper, performance of FC-TCR, STATCOM, TCSC, SSSC and UPFC are analysed.

Power electronic controllers were first introduced in HVDC transmission for improving power flow and system stability. There are four types of controllers in FACTS device family. Series controllers are used to inject voltage in series with the line and directly control voltage and current, which helps in controlling the power flow. Shunt type FACTS device are used for controlling and damping voltage oscillations in a power system. The benefits of employing FACTS are many: improvement of the dynamic and transient stability, voltage stability and security improvement, less active and reactive power loss, voltage and power profile improvement, power quality improvement, increasing power flow capability through the transmission line, voltage regulation and efficiency of power system operation improvement, steady state power flow improvement, voltage margin improvement, loss minimization, line capacity and loadability of the system improvement [21]. FACTS controllers are divided into four categories:

Shunt controller:- TCSC, TCPAR and SSSC,

Series controller:- STATCOM and SVC, Series-Series controller- IPFC

Series-Shunt controller:-UPFC, IPFC etc.

This paper deals with five FACTS devices (FC-TCR, STATCOM, TCSC, SSSC and UPFC).

2. Literature review

Research works are going on in finding newer concept for minimizing the reason of voltage collapse by increasing voltage stability (Dynamic, Transient and Steady-state stability), voltage margin and voltage security in the system. Voltage collapse is a major problem of power system and it occurs due to voltage instability. There are many analysis methods for determining voltage stability based on power flow. Steady- state stability is the ability of power system to control after small disturbances e.g.:- change in load [4]. In [6], dynamic performance of two area power system with and without UPFC have been studied and compared with other FACTS (Flexible alternating current transmission system) devices. Various types of FACTS controllers and their performance characteristics have been described in [6]. It is essential to analyse voltage stability for a secure power system. Static VAR compensator (SVC) and Thyristor controlled series capacitor (TCSC) increased system stability by placing SVC Flexible AC transmission system controller at different places steady- state stability of system can improved [7].

FACTS (Flexible alternating current transmission system) are mainly used for solving instability problems. Recently it has been noted that FACTS controllers can also be used for power flow control and stability enhancement control. Use of FACTS controllers for improving transient stability of a system has been investigated in [8]. Comparison of the performances of shunt capacitor, FC-TCR type SVC,and STATCOM using MATLAB/SIMULINK software has been done in[9]. In [10] the effect of SVC and STATCOM for static voltage stability margin enhancement is studied. Simulation and comparison of various FACTS devices (FC-TCR, UPFC) using Program with integrated circuits Emphasis (PSPICE) software has been done in [11] showing power transfer control.

In [12], how FACTS devices are used for power quality improvement and finally improve impedance, current and voltage in improving power system operation have been studied. In [14], modelling and simulation of SSSC multi-machine system for power system stability enhancement is studied. In [16] saddle node bifurcation analysis is applied for finding optimal location of SVC and TCSC, power flow is used to evaluate the effect of FACTS device on system loadability.

In this paper modelling and simulation of various FACTS (Flexible alternating current transmission system) devices have been done using MATLAB/SIMULINK software. These FACTS devices (FC-TCR, STATCOM, TCSC, SSSC, and UPFC) are controlled by controlling their source and line impedance value. First we determined the impedance value for better system performance. By varying the value of capacitor of all the above FACTS device models real and reactive power flow through the system is tabulated to find the FACTS device which gives better performance for a particular capacitor value.

3. Basic description of FACTS devices

3.1. Fixed capacitor thyristor controlled reactor (FC-TCR)

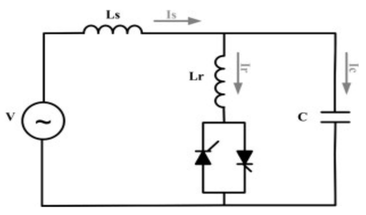


Figure1: Fixed capacitor thyristor controlled reactor

Static VAR compensated FACTS device are the most important device and have been used for a number of years to improve voltage and power flow through the transmission line by resolving dynamic voltage problems. SVC is shunt connected static generator/absorber. Utilities of SVC controller in transmission line are many: a) provides high performance in steady-state and transient voltage stability control, b) dampen power swing, c) reduce system loss, d) Control real and reactive power flow.

Simple FC-TCR type SVC configuration is shown in figure 1. In FC-TCR,a capacitor is placed in parallel with a thyristor controlled reactor. Is, Ir and Ic are system current, reactor current and capacitor current respectively which flows through the FC-TCR circuit. Fixed capacitor- Thyristor controlled reactor (FC-TCR) can provide continuous lagging and leading VARS to the system [5]. Circulating current through the reactor (Ir) is controlled by controlling the firing angle of back-back thyristor valves connected in series with the reactor. Leading var to the system is supplied by the capacitor. For supplying lagging vars to the system, TCR is generally rated larger than the capacitor.

3.2. Static synchronous compensator(STATCOM)

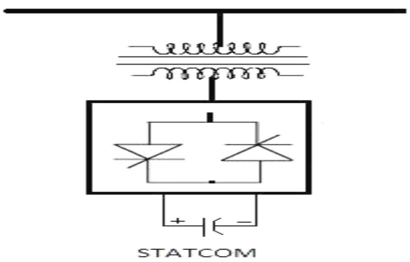


Figure 2: Static synchronous compensator

The static synchronous compensator (STATCOM) is another shunt connected GTO based FACTS device. STATCOM is a static synchronous generator operated as a static VAR compensator which can inject lagging or leading var into the system. STATCOM have several advantages. It has no rotating parts, very fast in response, requires less space as bulky passive components are eliminated, inherently modular and relocatable, less maintenance and no problem as loss of synchronism [5].Simple diagram of STATCOM is shown in figure [2].The dc source voltage is converted into ac voltage by the voltage source converter using GTO and ac voltage is inserted into the line through the transformer. In heavy loaded condition if. Output of VSC is more than the line voltage, converter supplies lagging VARs to the transmission line. During low load condition if line voltage is more than then converter absorbs lagging VAR from the system. If o/p voltage of converter is equal to line voltage, then the STATCOM is in floating condition and this shunt device does not supply or absorb reactive power to the system or from the system.

3.3. Thyristor controlled series capacitor (TCSC)

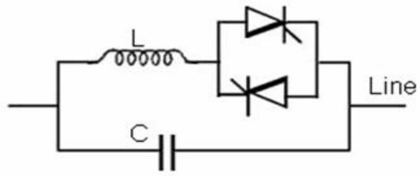


Figure 3: Thyristor controlled series capacitor

Thyristor controlled series capacitor (TCSC) is very important series compensator like SSSC. Specially in this FACTS (Flexible alternating transmission system) device, thyristor with gate turn-off capability is not required. Figure 3 shows schematic diagram of a TCSC controller. In TCSC, capacitor is inserted directly into the transmission line and TCR are mounted in parallel with the capacitor. As the capacitor is inserted in series with the line, there is no need of using high voltage transformer and thus it gives better economy. Firing angle of back to back thyristors are controlled to control the reactor. At 180° firing angle TCR, is non-conducting and at 90° firing angle TCR is in full conduction [4].

3.4. Static synchronous series compensator (SSSC)

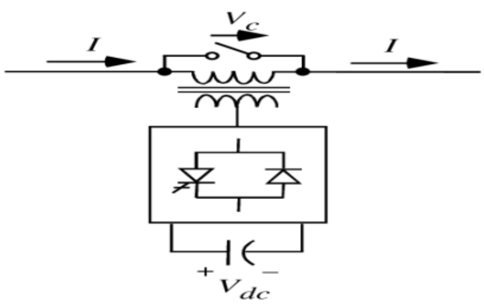


Figure 4: Static synchronous series compensator

In present days, SSSC is one of the most important FACTS controller used for series compensation of power. In series compensation the capacitor which is connected in series compensates the inductive reactance of the transmission line. SSSC output voltage (V_c) is in quadrature with the line current (I). The voltage across series capacitor is $-jX_cI$ (where Xc is the capacitive reactance of the series capacitor) and voltage drop across line inductance (X_L) is $+jX_LI$ cancel each other thus reducing the effect of line inductance. Due to this, power transfer capability is increased [5].The symbolic representation of SSSC using voltage source converter is shown in figure 4. Supply voltage from a dc source is converted into ac voltage using VSC (voltage source converter). Quadrature voltage is injected into the line through a coupling transformer. This injected voltage (Vc) lags the line current (I) by 90ºand series compensation is done. SSSC control flow of real and reactive power through the system.

3.5. Unified power flow controller (UPFC)

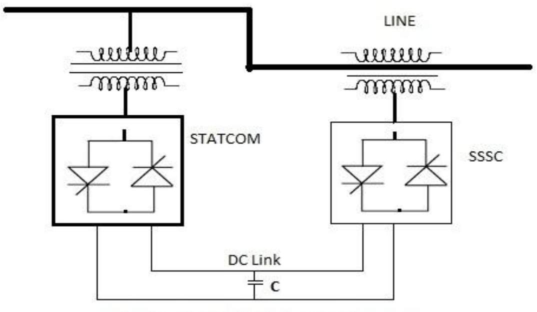


Figure 5: Unified power flow controller

Figure [5] shows a schematic diagram of UPFC. Full form of UPFC is Unified power flow controller. The word unified signifies all parameters (e.g.- voltage, phase angle, impedance, real and reactive power and power factor) which effect power flow in the system can be controlled [5]. UPFC is the most modernised device among all the FACTS devices which can be used to enhance steady-state stability, dynamic stability, real and reactive power flow and so on. UPFC consists of two converters. One converter (SSSC) is connected in series with the transmission line and other converter (STATCOM) is connected in parallel with the transmission line. The two converters are coupled through a common dc link which provides bidirectional flow of real power between series o/p SSSC and shunt output STATCOM respectively. For balancing of power between series and shunt controller it is necessary to maintain constant voltage across the dc link. Series branch (SSSC) of the UPFC injects variable magnitude voltage and phase angle. This improves power flow capability and transient stability [6].Shunt branch (STATCOM) maintains the balance between the real power absorption from or injection into the system.

4. Performance analysis of FACTS devices

4.1. Uncompensated system model

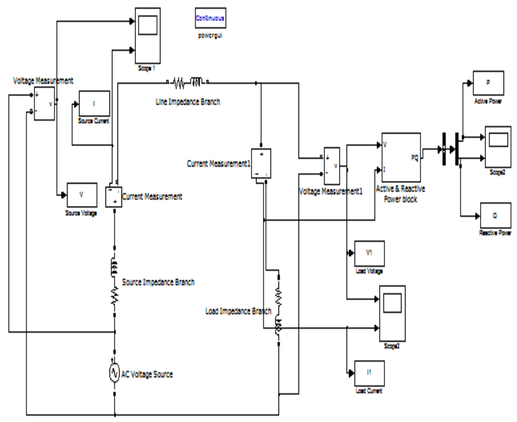


Figure 6: Uncompensated System

Figure [6] shows the basic transmission (11kV) model of an uncompensated system. This model consists of current measurement block, voltage measurement block, real and reactive power block and scopes. 11kv voltage is supplied from the AC voltage source to the system. Source impedance (0.01+0.001) Ω, Line impedance (5+0.023) Ωand load is kept constant at 25MW and 50MVAR for the above transmission line model. Simulation is done using MATLAB/SIMULINK. Current measurement block is used to measure the instantaneous source and load current flowing through the transmission line, Voltage measurement block is used to measure the source and load voltage. Real and reactive power in load side is measured using active and reactive power measurement block. Scopes display results after simulation. Above model provides three scopes: one displays the source voltage (V) and source current (I), second one displays real (P) and reactive (Q) power and third one displays load voltage (V_1) and load current (I_1) after simulation. Real and reactive power flows obtained after simulation are shown in below:

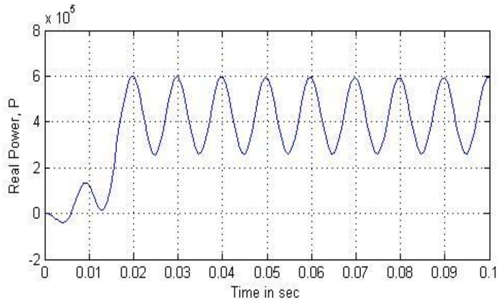


Figure 7: Real power flow

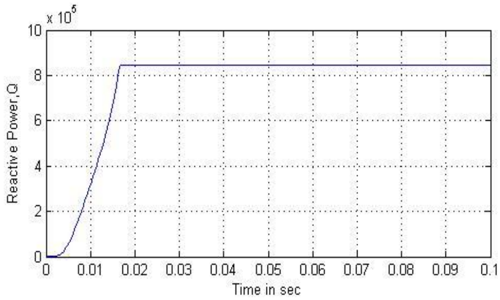


Figure 8: Reactive power flow

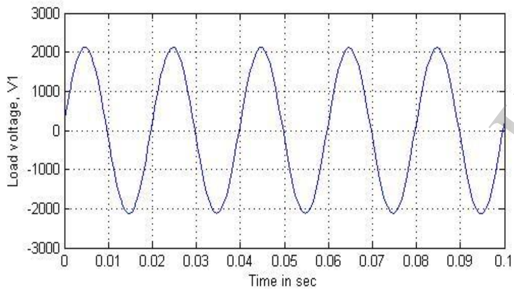


Figure 9: Load voltage

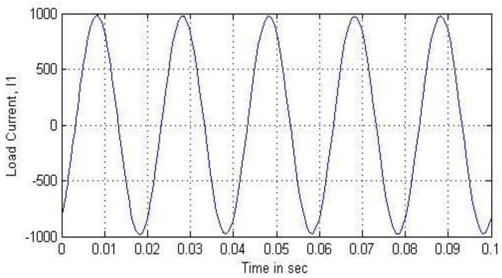


Figure 10: Load current

Load voltage is found to be 2.1 kV. Real and reactive power flow is obtained without any compensation. So, in order to keep the system stable, we have to provide reactive power compensation. In this paper, to get better performance regarding voltage stability, five compensating devices have been studied and comparison has been done to find the device that gives best performance under a given operating condition.

All the plots for the compensated systems have been shown for a particular capacitor value of 350μF.

4.2. Compensated system

4.2.1. FC-TCR Compensated. The SIMULINK model of FC-TCR (SVC) with line voltage of 11KV is shown below:

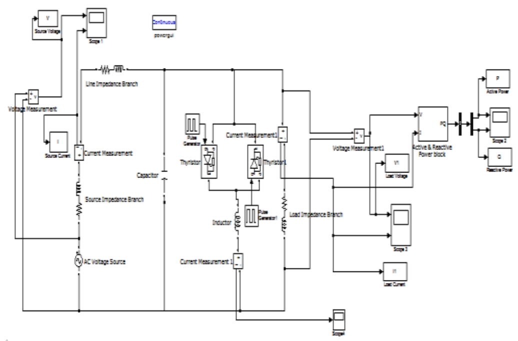


Figure 11: FC-TCR compensated system

Line impedance is kept at (0.01+0.001) Ω and load is fixed at 25MW and 50MVAR. Results obtained after simulation of FC-TCR model is shown below:

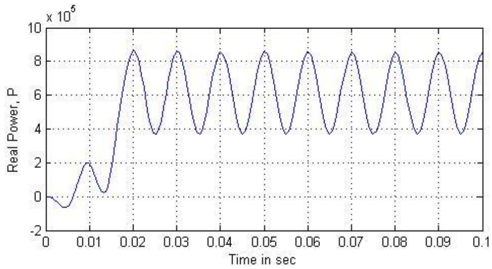


Figure 12: Real power flow

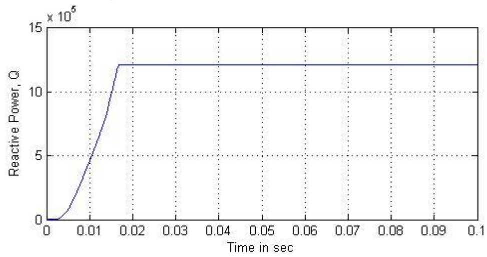


Figure 13: Reactive power flow

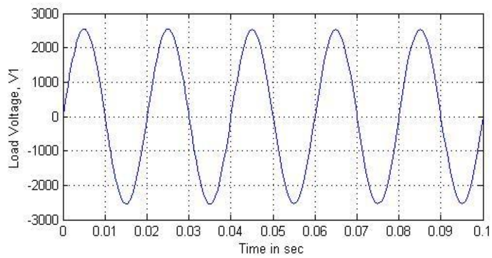


Figure 14: Load Voltage

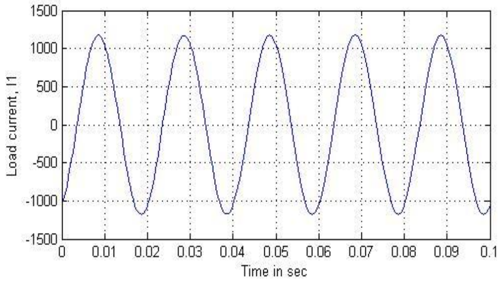


Figure 15: Load current

Real and reactive powers have been obtained for a fixed value of TCR inductance (100mH) and for different values of the capacitor. Improvement obtained in real and reactive power with changes in capacitor values are tabulated below:

Table 1: Variation of power flow with change in capacitance

SL No	Capacitance (μF)	Real power(MW)	Reactive power (MVAR)
1	50	0.628	0.886
2	200	0.733	1.03
3	350	0.86	1.21
4	500	1.02	1.43
5	600	1.14	1.60
6	800	1.44	2.03
7	1000	1.81	2.56
8	1200	2.22	3.15
9	1400	2.58	3.64
10	1500	2.70	3.80

Thus from the above table we see that power flow through the system increases proportionally with increase in capacitance. Real power varies from 0.628MW to 2.70MW and reactive power varies from 0.886MVAR to 3.80MVAR with variation in capacitance value. In this system results have been obtained by varying the capacitor value from 50 μF to 1500 μF.

4.2.2. STATCOM compensated system

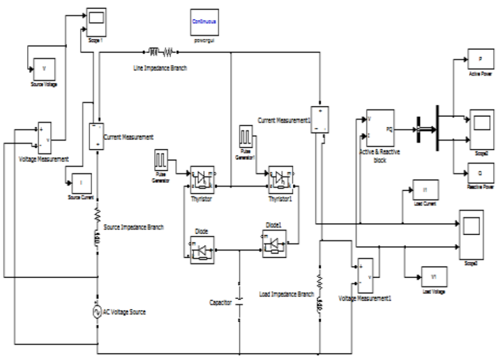


Figure 16: STATCOM compensated system

The above figure shows the compensated model of static synchronous compensator. The model is compensated for various capacitance values. For a particular value of capacitance (350μF) plots for real power (P), reactive power (Q), load voltage (V_1) and load current (I_1) are shown below:

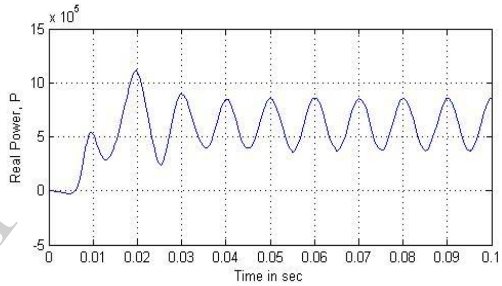


Figure 17: Real power flow

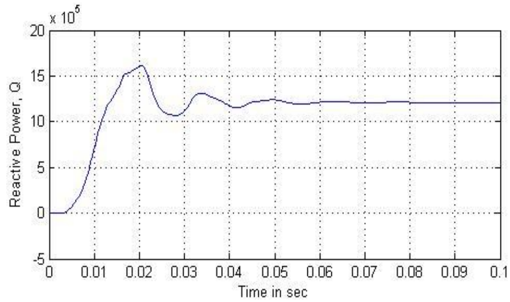


Figure 18: Reactive power flow

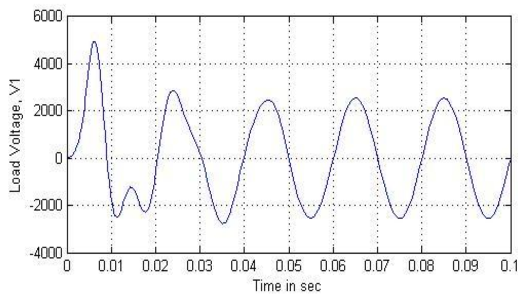


Figure 19: Load voltage

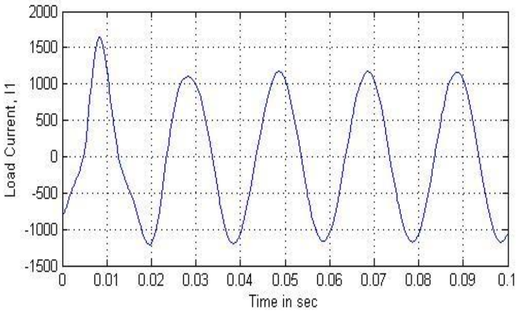


Figure 20: Load current

Real and reactive power flows obtained by varying the capacitor value till 1500µF are tabulated below:

Table 2: Variation of power flow with change in capacitance

SL NO	Capacitance (µF)	Real power (MW)	Reactive power(MVAR)
1	50	0.60	0.90
2	200	0.73	1.025
3	350	0.85	1.20
4	500	1.0	1.42
5	600	1.135	1.6
6	800	1.43	2.05
7	1000	1.8	2.5
8	1200	2.235	3.12
9	1400	2.6	3.68
10	1500	2.7	3.82

Thus we see that increase in the value of capacitance results in the improvement of both real and reactive power flows thereby compensating the system to a large extent. At capacitance value of 1500µF, compensator injects more real (2.7MW) and reactive (3.82MVAR) power to the system and receiving end voltage obtained is 4.5 kV. At this point STATCOM will inject more reactive power than SVC.

4.2.3. Thyristor controlled series capacitor compensated system. The circuit model used for simulation is shown below:

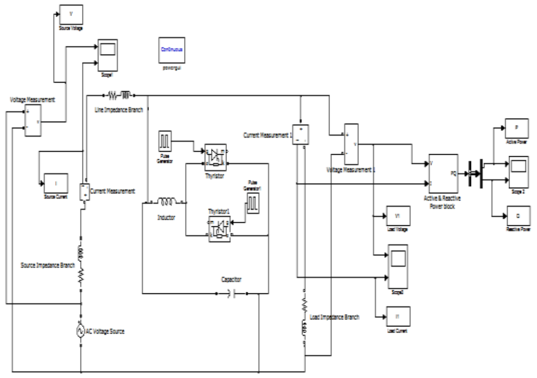


Figure 21: TCSC compensated system

The above model shows a Thyristor Controlled Series Capacitor connected to the system. In TCSC simulation model, inductor is fixed at 100mH and results are obtained for different capacitor values. Resultsobtainedafter simulation is shown below:

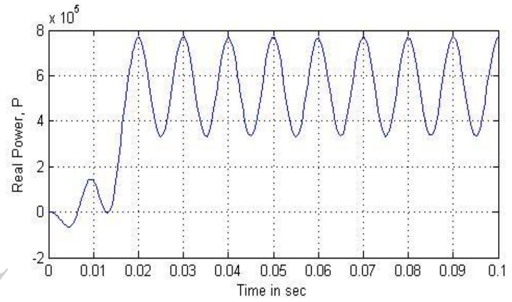


Figure 22: Real power flow

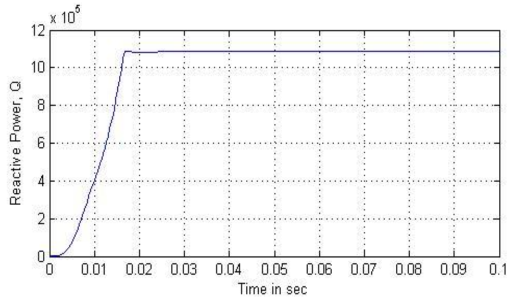


Figure 23: Reactive power flow

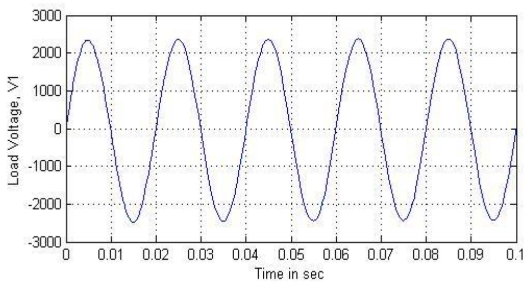


Figure 24: Load voltage

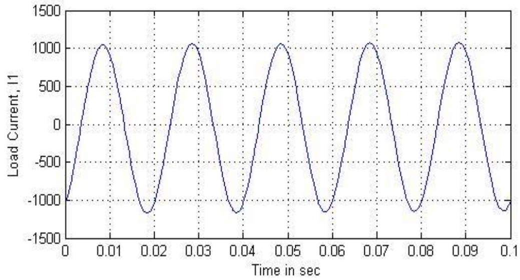


Figure 21: Load current

Above graphsare plotted when model is simulated with capacitor value 350µF.The plots show the improvement in the load voltage (V_1), load current (I_1), real power (P) and reactive power (Q) with the incorporation of TCSC in the system. Results obtained for different capacitor values of the controller are tabulated below:

Table 3: Variation of power flow with change in capacitance

SL No	Capacitance (µF)	Real power (MW)	Reactive power (MVAR)
1	50	0.57	0.805
2	200	0.66	0.93
3	350	0.772	1.085
4	500	0.91	1.28
5	600	1.02	1.43
6	800	1.27	1.80
7	1000	1.65	2.30
8	1200	2.03	2.85
9	1400	2.52	3.5
10	1500	2.66	3.7

From the above table we can see that increasing the value of capacitance results in continuous compensation of real and reactive power without deterioration. Receiving end voltage improves from 2 kV to 3.8 kV.Voltage profile improves up to a certain point depending on capacitance value.

4.2.4. Static synchronous series compensated system. The model of the SSSC compensated system is shown below:

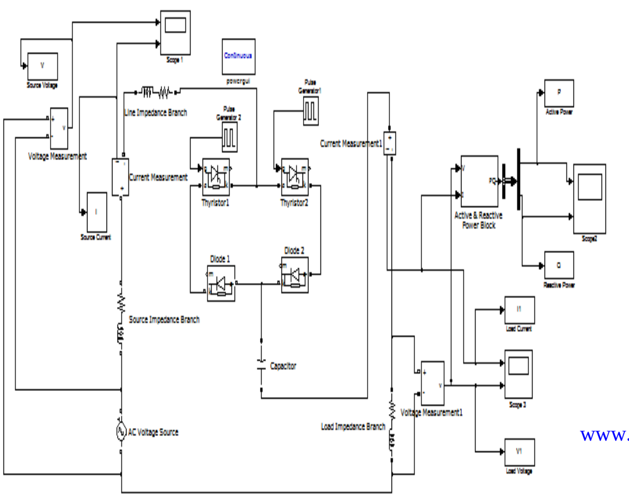


Figure 22: SSSC compensated system

The above configuration shows the compensated model for Static SynchronousSeries Compensator (SSSC) connected to the system. Real and reactive powers are obtained by varying the value of capacitance connected in series with the line. Plots for power and voltage profiles are shown below:

Figure 23: Real power flow

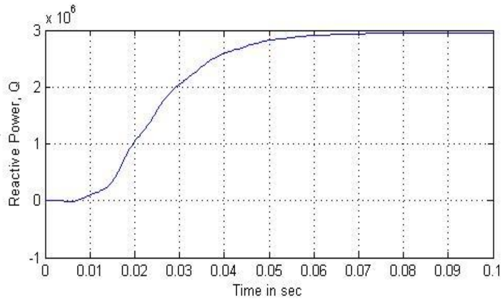


Figure 28: Reactive power flow

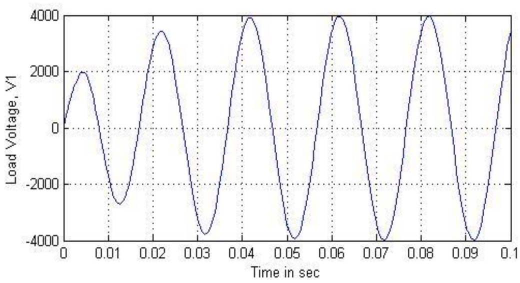


Figure 29: Load voltage

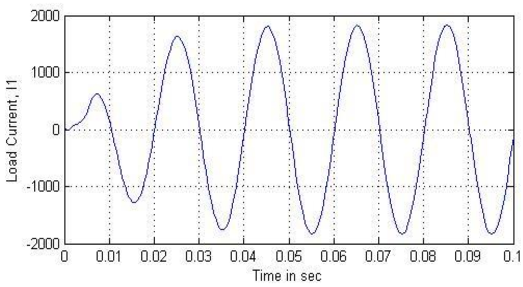


Figure 30: Load current

Plots for a particular value of capacitance (350 μF) are shown above. Real and reactive power variation with change in capacitance values are tabulated below:

Table 4: Variation of power flow with change in capacitance

SL No	Capacitance(μF)	Real power (MW)	Reactive power (MVAR)
1	50	0.025	0.036
2	200	0.985	1.38
3	350	2.08	2.93
4	500	1.65	2.34
5	600	1.40	2.00
6	800	1.13	1.60
7	1000	1.00	1.4
8	1200	0.9	1.28
9	1400	0.85	1.21
10	1500	0.83	1.18

From the above table we can see real and reactive power increases with the introduction of capacitance. But, it is also noted that compensation occurs up to a capacitor value of 350μF only.If the capacitance is increased beyond this point, then real and reactive power both deteriorates. So, better compensation is obtained ata capacitor valueof 350μF for this system.

4.2.5. UPFC compensated system

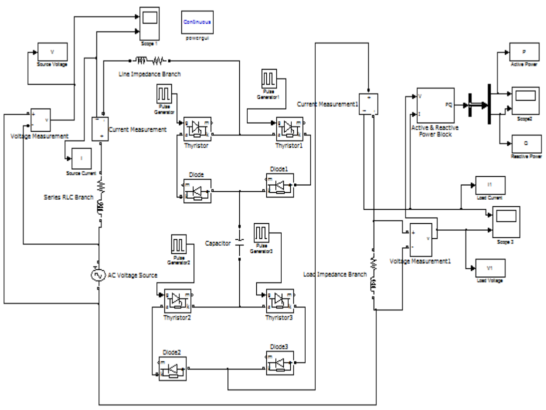


Figure 31: UPFC compensated system

The above circuit shows the basic model of UPFC (unified power flow controller) connected to the system. Graphs obtained after simulation are shown below

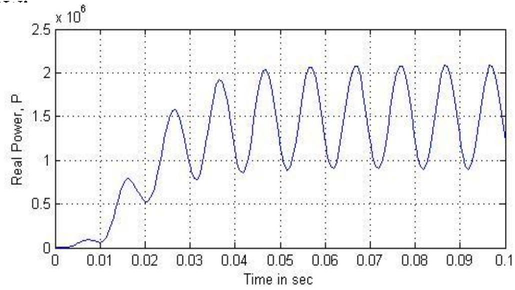


Figure 32: Real power flow

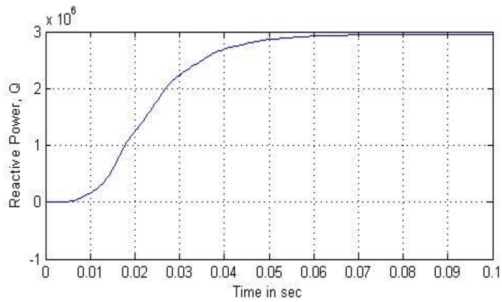


Figure 33: Reactive power flow

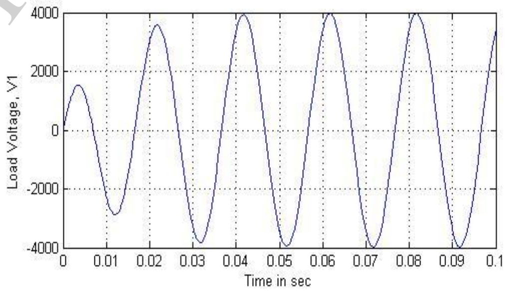


Figure 34: Load voltage

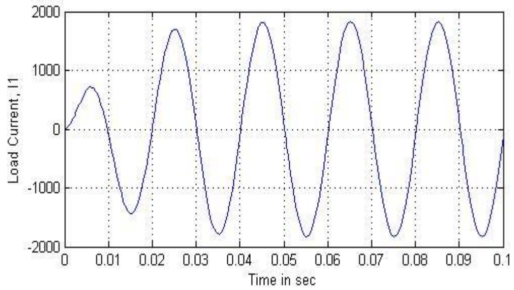


Figure 35: Load current

The above graphs show real, reactive and receiving end voltage improvement using compensation. Graphs obtained for a particular value of capacitor rating (350uF) are shown above. Power flows obtained with change in capacitance are tabulated below:

Table 5: Variation of power flow with change in capacitance

S L No	Capacitance (µF)	Real power (MW)	Reactive power (MVAR)
1	50	0.0254	0.036
2	200	0.975	1.38
3	350	2.08	2.95
4	500	1.64	2.33
5	600	1.4	1.98
6	800	1.13	1.60
7	1000	1.0	1.40
8	1200	0.91	1.285
9	1400	0.85	1.20
10	1500	0.83	1.17

From the above table, it is seen that both power flows is improved up to a certain limit of capacitance (350µF). In this point injection of real and reactive power to the system is maximum. Beyond this, if we increase the value of capacitance then power profile is deteriorates. So, we can conclude that desirable performance is obtained at capacitor rating 350µF for UPFC compensated system.

4.3. Comparison between all FACTS devices

Table 6: Comparison of power flow between above FACTS Devices

FACTS Device	Capacitance (350µF) Real power(MW)	Capacitance (350µF) Reactive power(MVAR)	Capacitance (1500µF) Real power(MW)	Capacitance (1500µF) Reactive power(MVAR)
FC-TCR	0.86	1.21	2.70	3.80
STATCOM	0.85	1.20	2.70	3.82
TCSC	0.772	1.085	2.66	3.70
SSSC	2.08	2.93	0.83	1.18
UPFC	2.08	**2.95**	0.83	1.17

From the above table, it is seen that reactive power improvement will vary with change in capacitance in all the five cases. At a capacitor value of 350µF UPFC is seen to give best performance and at capacitor value 1500µF, STATCOM gives better performance. Since, increased rating of capacitor means increase the cost of equipment. So, from the above comparison table we can conclude that UPFC FACTS controller will give optimum performance at capacitor rating of 350µF.

5. Result and discussion

5.1. FC-TCR type SVC compensation:

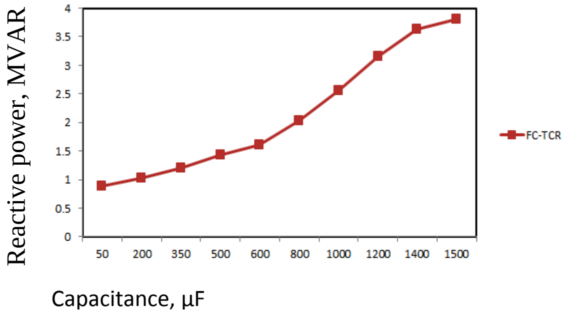


Figure 36: Variation of power flow with change in capacitance (50-1500µF)

The above graph shows the variation of reactive power profile with change in capacitance for an FC-TCR type SVC connected to the system. Reactive power flows improves proportionally with increase in capacitance value. In this case, optimum performance is obtained for capacitor value of 1500µF.

5.2. STATCOM Compensation

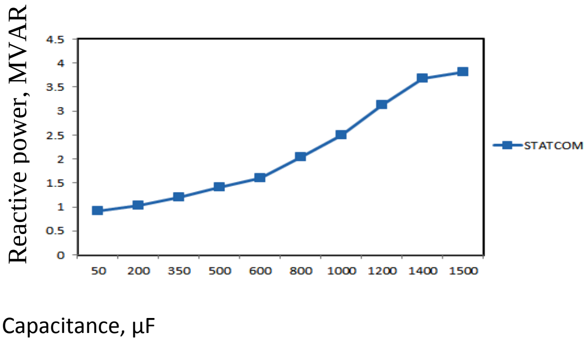


Figure 37: Variation of power flow with change in capacitance (50-1500µF)

Above graph shows the variation of reactive power for different capacitor values for a STATCOM connected to the system. Increasing the value of capacitance result in continuous compensation of reactive power.

TCSC Compensation

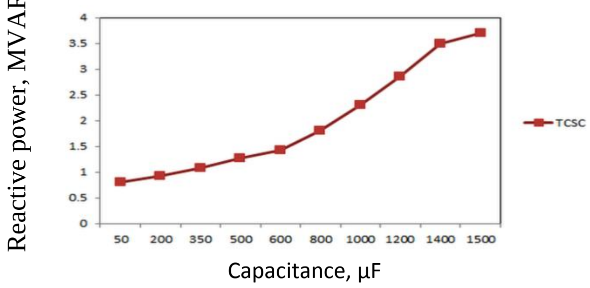


Figure 38: Variation of power flow with change in capacitance (50-1500µF)

Above graph shows compensation of the system for varying capacitor values when a TCSC is connected to it. We can see that increase in the value of capacitance results in improvement of reactive power. In this case, a capacitor value of 1500µF gives best performance.

5.4. SSSC Compensation

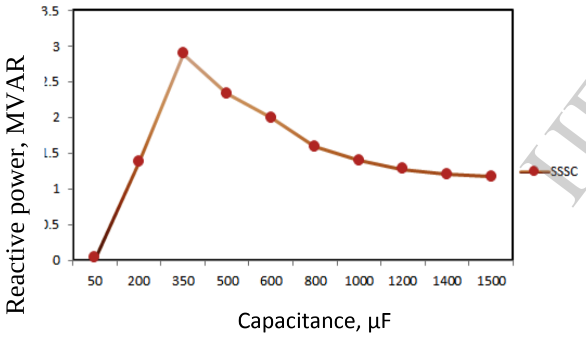
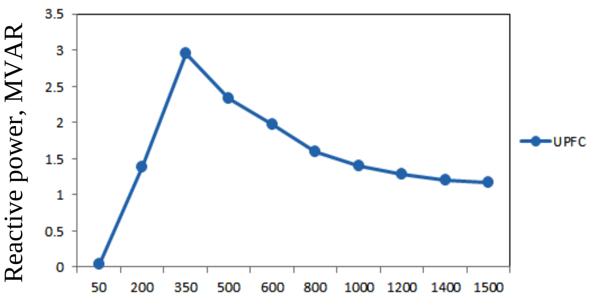


Figure 39: Variation of power flow with change in capacitance (50-1500µF)

The above graph [39] shows reactive power improvement after compensating the system using SSSC. It is seen that reactive power improves only up to a certain value of capacitance (350µF) beyond which it deteriorates.

5.5. UPFC Compensation



Capacitance, µF**Figure 40: Variation of power flow with change in capacitance (50-1500µF)**

From the above graph [40] it is clear that reactive power flow is improved impressively up to a capacitor rating of 350µF beyond which it deteriorates.

6. Comparison of power flow between above FACTS devices

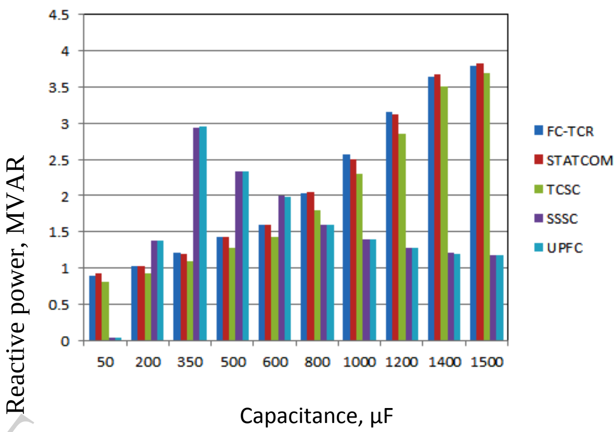


Figure 41: Variation of power flow between above FACTS devices with change in capacitance (50-1500µF)

The above graph shows the behaviour of all the FACTS devices for different capacitor values. From this graph, it is observed that, of all FACTS devices, UPFC gives best performance for a capacitor value of 350µF after which its performance deteriorates. Again we see, that the performance of STATCOM continues to improve with increasing capacitance. But, increasing the capacitor rating means increasing the overall cost of the equipment. So, after comparing the performances of all the five FACTS devices,it can be concluded that desirable performance is obtained with the addition of UPFC to the system for a capacitor value of around 350 µF, all other parameters remaining unchanged.

7. Conclusion

MATLAB/SIMULINK environment is used for this comparative study to model and simulate FC-TCR type SVC, STATCOM, TCSC, SSSC, and UPFC connected to a simple transmission line. This paper presents performance analysis of all the above FACTS devices and an elaborate comparison between their performances. Power flow and voltage profile are seen to improve with all the compensating devices. Results show that in case of FC-TCR and STATCOM compensation, reactive power flow improves proportionally with increasing capacitance and is maximum at maximum value of capacitance (1500 µF here).In case of TCSC a fixed inductance of 100mH and capacitor value of 1500µF gives best result. For SSSC compensation a capacitor rating of 350µF yields best result. For UPFC, a capacitor rating of 350µF gives bestresults. Voltage compensation using all the FACTS devices have also been studied. UPFC, SSSC and STATCOM,allare found to give desirable performances under given operating conditions. UPFC and SSSC gives their best performance at a capacitor value of 350µF, but UPFC gives the best performance amongst these two.But STATCOM fails to give any impressive performance at this point. However, its performance continues to improve with increase in capacitance and it starts giving better performance than UPFC and SSSC only after its capacitor value is kept around 1200µF. it gives optimum performance at the maximum capacitor value, i.e. 1500µF. FC-TCR type SVC provides compensation from a capacitor value as low as 50µF but gives better performance only at a high value of capacitance. Its best performance is achieved at the maximum capacitor value i.e. 1500µF. TCSC behaves in a similar way as SVC and gives best performance at 1500µF. If rating of capacitor is increased then cost of the equipment is also increased. Hence, it can be concluded that UPFC provides most desirable performance when connected to the system as compared to other FACTS devices.

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