Quantifying Losses in Power Systems Using Different Types of FACTS Controllers

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by

Gopiram Maddela

Saskatoon, Saskatchewan, Canada

Permission to Use

Head of the Department of Electrical and Computer Engineering
57 Campus Drive
University of Saskatchewan
Saskatoon, Saskatchewan, Canada
S7N 5A9

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– Gopiram Maddela

[1]Kalyan K Sen (Ph.D., P.E.), Sen Engineering Solutions, Pittsburgh, USA.

Abstract

This thesis discusses the placement of conventional power flow controllers (namely the Fixed series capacitor (FSC), Phase Angle Regulating Transformer (PAR)) and Flexible AC Transmission System (FACTS) devices (namely the Thyristor Controlled Series Capacitor (TCSC), the Static Synchronous Series Compensator (SSSC), the Unified Power Flow Controllers (UPFC) and the Sen Transformer (ST)) in bulk power systems to minimize transmission losses in the entire system. This firstly resolves line overloading and improves the overall voltage profile of the entire system. Secondly the transmission losses are minimized and also help in reducing the generation, which results in additional dollar savings in terms of the fuel costs.

The sizes of the FACTS devices used were small in order to keep the initial installation costs low for the utility. The reduced FACTS device ratings are mentioned as a benefit, but not included in the overall loss minimization calculations. Various types of FACTS devices were modeled and placed in the power system, and the economic benefits were discussed and compared for different power flow conditions.

The FSC, PAR, TCSC are the FACTS Devices commonly used in the electric utility industry. In addition to the previous devices the SSSC and UPFC were also modeled in the popular PSS/E[2] and PSAT [3] softwares. The Sen Transformer was modeled using an electromagnetic transient simulation program (PSCAD/EMTDC[4]). A line stability index was used to find the optimum location for placing the FACTS device. This thesis also provides a quantified value for the overall losses with the different FACTS devices, which is not available in the previous research literature.

[2]PSS/E^{TM}, Power System Simulator for Engineering is the registered trademark of Siemens, Canada.

[3]PSAT^{TM}, Power Flow and Short circuit Assessment Tool is the registered trademark of Powertech Labs INC, Canada.

[4]PSCAD/EMTDC^{TM} is the registered trademark of Manitoba HVDC Center, Winnipeg, Canada.

The Sen Transformer is a new type of a FACTS device that was developed by a former Westinghouse engineer, Dr. Kalyan Sen in 2003. It is based on the same operating principle as a UPFC (i.e. provides independent active and reactive power control) but uses the proven transformer technology instead. The benefit of the SEN transformer is that it would cost approximately only 30% of the UPFC cost. This thesis studies the Sen Transformer for loss minimization. Since the Sen technology uses a mature transformer technology, its maintenance costs are going to be less and therefore the utilities would be more comfortable using such a device instead of UPFC.

A 12 bus test system proposed by FACTS modeling working group was used for validating and testing the FACTS devices in this thesis. This test system is a composite model of Manitoba Hydro, North Dakota, Minnesota, and Chicago area subsystems. This test platform manifests number of operating problems, which the electric utilities typically face. This system has been used for congestion management, voltage support and stability improvement studies with the FACTS devices. The results show that compensating a short transmission line in this system is more effective in minimizing the overall losses and improving the voltage profile compared to a typical approach of compensating long lines. The results also show that the UPFC and Sen Transformer are the most effective in minimizing the overall losses with the Sen Transformer being the most cost effective solution.

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List of Symbols and Abbreviations

Symbol	Description
E_{Thev}	Thevinin equivalent source voltage
f_{ref}	The frequency of the reference signal (60 Hz)
I_c	Current passing through capacitor branch
I_L	Current passing through inductor branch
I_T	Total current through line
L_{mn}	Line stability index
P_R	Receiving end power
P_S	Sending end power
Q_R	Receiving end reactive power
Q_S	Sending end reactive power
V_0	Input voltage to the converter
V_c	Voltage across Capacitor
V_q	Quadrature voltage
V_R	Receiving end voltage
V_S	Sending end voltage
V_{Series}	voltage injected through series component (ex: TCSC, SSSC and IPFC etc.)
V_{Shunt}	voltage injected through shunt component (ex: STATCOM , SVC etc.)
X_c	Capacitive Reactance
X_{comp}	Line impedance after compensation
X_L	Transmission line impedance
X_T	TCSC inductor impedance
Z_L	Thevinin equivalent load
Z_{Thev}	Thevinin equivalent line impedance
α	Thevinin equivalent source phase angle
δ	Power angle

Abbreviation	Description
BFA	Bacteria foraging algorithm
CSC	Current source converter
EP	Evolutionary programming
EMTDC	Electro-magnetic transients & DC
EPRI	Electric power research institute
FACTS	Flexible AC transmission system
FSC	Fixed series capacitor
GA	Genetic algorithm
HPSO	Hybrid practical swarn optimization technique
IPFC	Interline power flow controller
IPSLP	Interior point successive linear programming
KEPCO	Korea electric power corporation
MOV	Metal oxide varistor
PAR	Phase angle regulating Transformer
PSAT	Power flow & short circuit assessment tool
PSCAD	Power system computer aided design
PSO	Practical swarn optimization technique
PSS/E	Power system simulator for engineering
PWM	Pulse width modulator
SIL	Surge impedance loading
SMES	Superconducting magnetic energy storage
SPC	Saskatchewan power corporation
SSSC	Static series synchronous compensator
STATCOM	Static synchronous compensator
ST	Sen transformer
SVS	Static VAr compensator
VSC	Voltage source converter
TCSC	Thyristor controlled series capacitor
TSSC	Thyristor switched series capacitor
UPFC	Unified power flow controller

Chapter 1

Introduction

1.1 Background

Average active power losses in a system account for 5% to 10% of its total generation. In the year 2010, the average of the transmission and distribution losses recorded in Canada was 10.8 % [1]. Utilities are experiencing more losses in the system with the growth of demand. These losses are mostly in the transmission lines. The transformers, loads and other power flow regulating devices have also their own internal losses but they are a smaller fraction of the total transmission system losses. The losses limit the desired transmission line power flow, cost millions and affect the economical operation of the deregulated utility environment. Considering the utility loss percentage and its other consequences, the reduction of losses in even a small percentage will lead to the achievement of economical operation and better system efficiency [2] [3] [4].

This loss minimization will regulate the loop or mesh flows in the transmission system and improve transmission efficiency between local or multi-area interconnected systems. The components, i.e. power flow controllers used for loss minimization will improve the power flow along with the required reactive power (VAr) support for the system. Advancement in the power electronics industry such as IGBTs has helped in increased rated controlling capacity and resolved operating and planning issues (both short-term and long-term). For example, 500 kV lines are also being compensated now-a-days.

The large rated power electronics' have high devices' costs, and several maintenance and operating issues. Several researchers have worked on new power electronic types that could be designed with lower device costs. The Sen transformer was introduced in the last decade and has been found to be an efficient power flow controller. This device works on simple transformer-based technology and provides operating features (independent active and reactive power control) similar to those of other power electronic devices. Its loss minimization functionality will be tested in a practical test system and compared to the others. Overall, the loss minimization of each power flow controller will be described in detail, compared to traditional practices, and concluded with discussion of its benefits.

1.2 Transmission Line Losses

The Saskatchewan Power Corporation (SPC) experienced 2172 GWh in line losses costing approximately $239 million in the year 2012. Multiple physical and operating factors like line resistance, inductance, capacitance, bundled conductors, low efficiency equipment, line length and voltages caused these losses in transmitted power. Minimizing or regulating some of these factors will improve the transmitted power flow, line losses and will reduce the unit price.

The major power loss occurring in transmission lines is due to line resistance. As explained in Equation 1.1, this losses will be minimized by using a higher voltage (i.e. low current) transmission system. But for medium and long transmission lines, the overall resistance is far lower compared to the transmission line impedance Z_L ($= R_L + jX_L$), which will generate or absorb reactive power and limits the active powerflow.

$$\text{Conductor ohmic loss (or) Thermal power loss } (P_{loss}) \text{ (in MW)} = \frac{1}{2}|I^2|R_L \tag{1.1}$$

Here I is the current flowing through conductor, R_L and X_L are the line resistance and reactance respectively.

Minimizing or compensating the transmission line impedance will regulate the reactive power flow and improve the active power flow through the line. Figure 1.1 explains a simple transmission system and the respective sending end voltage (magnitude and angle) and power (active and reactive) V_S, δ_S, P_S and Q_S, respectively. A similar receiving end voltage (magnitude and angle) and power (active and reactive) V_R, δ_R, P_R and Q_R are also shown. The other line loss driving factor, i.e. voltage, is strongly affected by the surge impedance

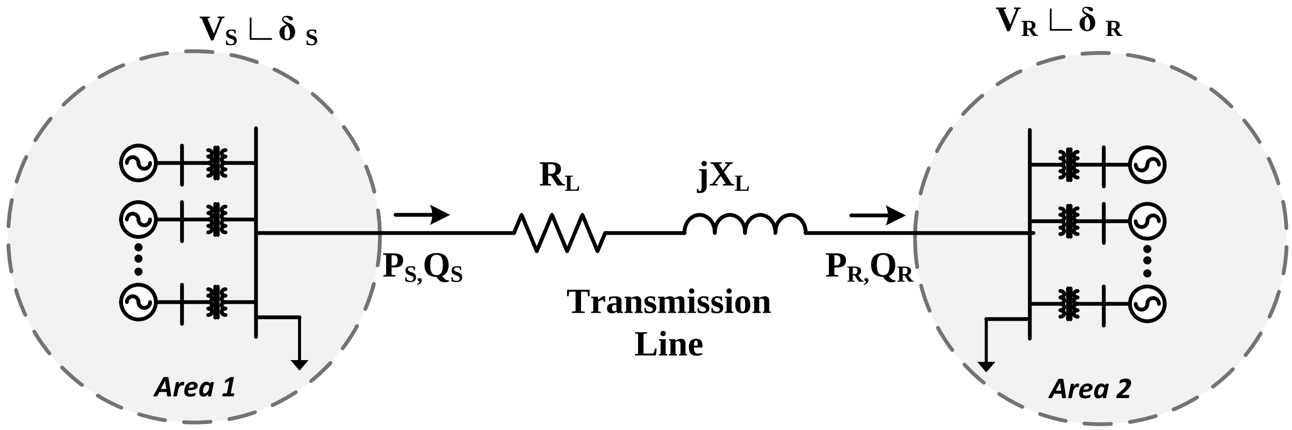


Figure 1.1: A simple two area system

loading equation explained in Equation 1.2, and will be explained in detail in the following Section 1.3.

$$\text{Surge Impedance (Z)} = \sqrt{\frac{L}{C}} \tag{1.2}$$

Here L and C are transmission line inductance and capacitance.

The proposed power flow controllers influence the transmission line impedance or voltages and minimize active losses. Chapter 2 explains the various power flow controllers on the market and their compensation techniques. The proposed transmission loss minimization will improve the overall efficiency of transmission as well as system efficiency. Equation 1.3 gives the overall efficiency improvement using the line compensation.

$$\text{Efficiency}(\eta(\%)) = \frac{P_R}{P_S} = \frac{P_R}{P_R + P_{loss}} \tag{1.3}$$

Here p_{loss} indicates the losses obtained in a line due to various phenomena, and P_S and P_R are sending end and receiving end transmitted active power quantities.

1.3 Voltage Profile

As discussed in the previous section, losses are also affected by the transmission line voltage profile of the system. Utility bus nominal voltages are regulated to ± 5% on the customer's end and must stay with-in ± 10% under all other operating conditions. SPC and BC Hydro real-time operation and electric service requirement documents refer to these limits [5]. Furthermore, areas with huge load and less generation will experience low voltage issues. Figure 1.2, refers to the relation between voltage drop, line current and power transfer in a transmission line. Since the losses are directly proportional to the line current, a voltage drop in the line will lead to higher losses. Also, in high voltage and extra-high voltage transmission lines, the allowable voltage drop is 5% to 10% of the sending end voltage.

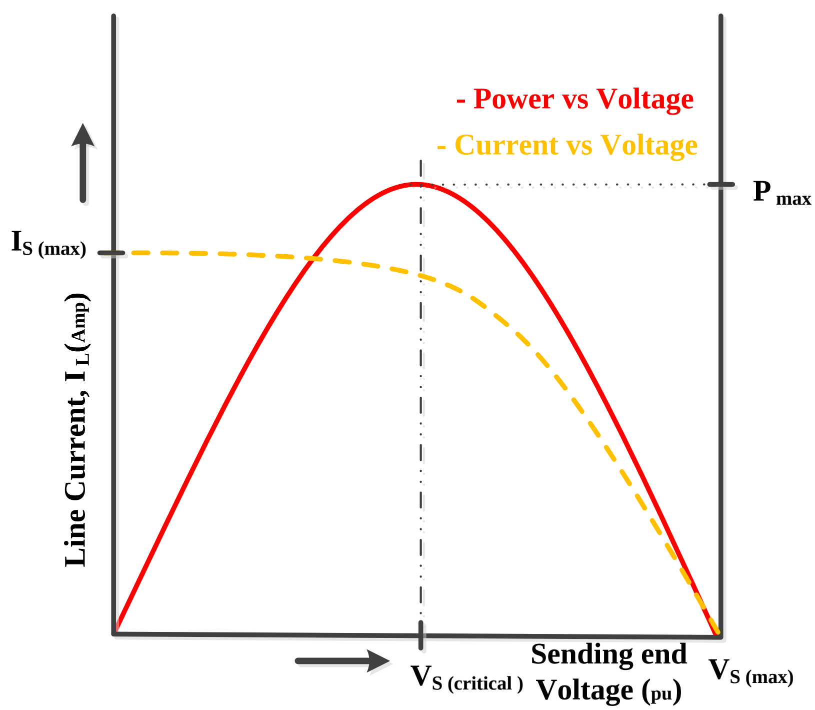


Figure 1.2: Relation between voltage, current and power

The available solution is either regulating voltage at the sending end bus or minimizing line resistance to transmit more active power. For medium and long transmission lines, line reactance and line capacitance will limit the power flow and cause low voltage issues in the system. The other factor, surge impedance loading, contributes to the voltage drop in the system. The transmission line power (P) measured in an ideal situation, or no reactive power loss, is called as the surge impedance loading (SIL) of the line. In short, the SIL derives from surge impedance (Z) and voltage (V_{l-l} (phase to phase)) as shown in Equation 1.4. As shown in Figure 1.3, operating above or below this limit causes over, or under, voltage ($V_{S'}$) (based on reactive power absorption or generation) along the line. This limits active power flow and causes higher losses due to transmission line loop flows. The resultant low voltage observed on the load terminals will again lead to low voltage issues in the system. Table 1.1 gives the typical transmission line parameters and required surge impedance loadings for better voltage regulations.

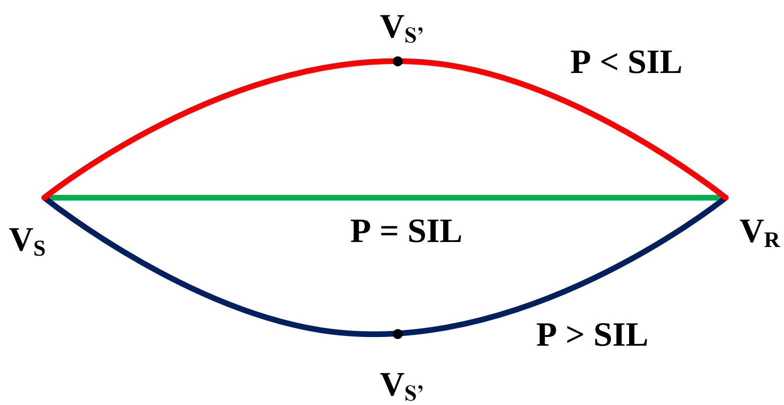


Figure 1.3: Effect of SIL on transmission line voltage

$$\text{SIL (in MW)} = \frac{kV_{l-l}^2}{Z} \tag{1.4}$$

Here V_{l-l} represents line to line voltage in kV and Z is the surge impedance. Similarly, Equation 1.5 denotes the calculation of surge impedance from transmission line impedance (L) and capacitance (C).

$$\text{Z (in }\Omega) = \sqrt{\frac{L}{C}} \tag{1.5}$$

Voltage (kV)	**Surge Impedance (Ω)**	**Resistance (Ω/km)**	**Inductance (Ω/km)**	**Charging (kVAr/km)**	**Surge impedance loading (MW)**	**X/R ratio**
69/72	370	.4	.5	15	13/14	1.2
138/144	370	.2	.5	70	50/55	2.5
230/240	340	.07	.45	225	170	6
230/240 (bundled)	300	.07	.4	290	180/195	6
345 (bundled)	285	.026	.365	525	415	14
500 (bundled)	250	.018	.345	1340	990	20

Table 1.1: Typical transmission line characteristics

Simple power flow Equations 1.6 and 1.7 determine the effect of voltage (proportional relationship) on the transmission power flow and the respective loss growth.

$$P_S = P_R = \frac{V_S V_R}{X_L} sin\delta \tag{1.6}$$

$$Q_S = -Q_R = \frac{V_S V_R}{X_L}(1 - cos\delta) \tag{1.7}$$

Here P_S, Q_S and P_R, Q_R represent the sending end and receiving end reactive power flows. Also, V_S, V_R are the sending and receiving end voltages with delta (δ) phase angle difference between both ends. Finally, X_L is transmission line impedance.

Since the transmission line impedance remain constant during steady state, the voltage magnitudes and phase angles will strictly control the power flow in the system. Improving this sending end and receiving end voltages will maximize the power flow through the desired path and limit the losses.

1.4 Transmission line over-loading

Transmission line over loading observed in a system is primarily due to loop flows and other line rating issues. Figure 1.4 explains the relation between line loading levels and line length with line flow limiting factors. Among these factors violating or operating close to thermal limits will cause an increase in line sag and even lead to conductor melt. The stability limit, or steady state stability limit, is the maximum MW that can be transferred in steady state without loss of synchronism [6]. Similarly, as discussed in Section 1.3, violating the voltage limit causes excessive line current and increase in system losses.

There is another disadvantage to overloading, as it will cause limitations in transfer power through the desired lines. In the current deregulated environment, the transmission line corridors are bottle necked and wheeling power would be costly. Table 1.2 refers to SaskPower non-firm point-to-point transmission service delivery costs [7]. To avoid these issues, one possible solution is building new transmission lines in parallel. Since this idea costs millions of dollars and will trigger public and environmental issues (land, right of way,

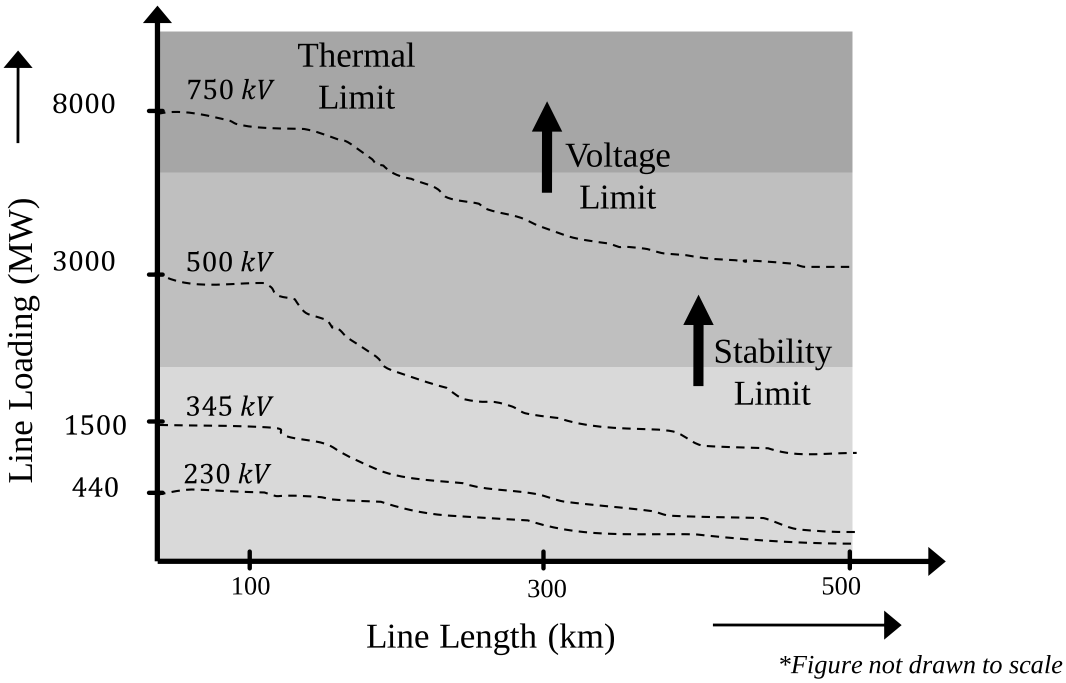


Figure 1.4: Transmission line loading with different voltage levels

Table 1.2: SaskPower non-firm point-to-point transmission service costs

Duration	**Cost (CAD $)**
Monthly delivery	2370/MW
Weekly delivery	547/MW
Daily delivery	109/MW
Hourly delivery	6.86/MW

etc.), another possible solution is to use a compensation device which will resolve the issue, reduce losses and provide economical operation of the system.

1.5 Optimal Location Selection

The discussion in the previous section on system operating limitations and issues presents the importance of powerflow controllers selection, installation and operation. Now to minimize losses and maximize power flow, power flow controller selection and optimal placement criteria will play a key role. Placing the device in an optimal location will reduce the unwanted loop flows in the system and provide the required active and reactive power for the system. Various power flow controllers and their working mechanisms are explained in Chapter 2. The device's placement will fine-tune the loss minimization, voltage profile and line loading issues in the system [8].

A line stability index approach is used in this thesis for optimal location selection. This approach gives a formulation for placing different FACTS devices in the system and resolves multiple objectives in the system, i.e. resolve the loop flows, improve the voltages, and minimize the losses, etc.

1.5.1 Line stability indices

The transmission line loading margin has been the most widely used and accepted technique to determine the transfer power capacity of a line. This technique predicts the low and high voltage scenarios in a system. PV and QV curves are used to determine the capacity of individual load buses in order to avoid low voltage issues. Between the two, the QV curve also determines the maximum reactive power that can be added or achieved at a certain load bus for economical operation. This same concept has been illustrated in detail by multiple authors to determine the inter-relation and requirements of active, reactive and load bus voltage limits.

M.Moghavvemi et al. [9] derived formulae for calculating a line stability index based on the power transfer through two busbars in an interconnected system. This stability index is used to predict stability and low voltage scenarios in the interconnected system. Multiple indices are formulated below, to determine the voltage collapse and power transfer stability, etc. Figure 1.5 illustrates the complex system to calculate the power transfer stability index, where the whole system is to be represented as a Thèvenin equivalent circuit. The resultant Thèvenin source voltage ('$E_{Thev}\angle\alpha$'), and branch impedance ('Z_{Thev}') are used for index calculation. For the above, line stability criteria are used for optimal location selection. An index (L_{mn}) value close to zero will indicate the location as most suitable for compensation, while a value closer to one will reflect the opposite. Equation 1.8 formulates the line stability indices of transmission line with line impedance ($X_L\angle\theta$) and other factors from simple power flow (obtained parameters), such as sending end voltage (V_S), phase angles (δ_S and δ_R), and receiving end reactive power (Q_R).

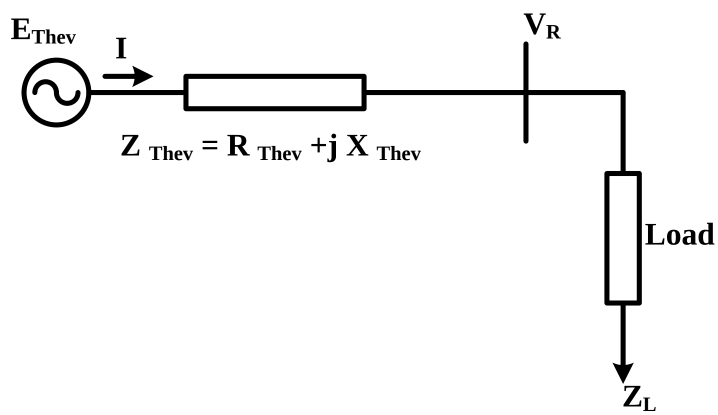


Figure 1.5: Thèvenin equivalent circuit

$$\text{Line stability index } L_{mn} = \frac{4X_LQ_R}{[V_S sin(\theta - (\delta_S + \delta_R))]^2} \tag{1.8}$$

Equation 1.9 demonstrates the power transfer stability index (PTSI) and uses the Thèvenin equivalent source values (voltage ($E_{Thev}\angle\alpha$), line impedance (Z_{Thev}) and load (Z_L)).

$$\text{Power transfer stability index PTSI} = \frac{2S_LZ_{Thev}[1 + cos(\delta_R - \alpha)]}{E_{Thev}^2} \tag{1.9}$$

$$\text{Where, } S_L = \frac{E_{Thev}^2 Z_L}{E_{Thev}^2 + Z_L^2 + 2Z_{Thev}Z_L cos(\delta_R - \alpha)} \tag{1.10}$$

1.6 Literature Survey

The previous sections highlighted the importance of loss minimization with power flow controllers without affecting the system limits to achieve economical operation. To achieve that loss minimization and maintain a stable system, adequate research has been done on device ratings and location selections with both algorithmic and practical approaches.

First, the technique-based loss minimization approaches will be explained in detail. These techniques basically derive from economic dispatch, because they use simple shunt compensation devices to achieve loss minimization. The majority of these studies are done in radial distribution systems where the loop power flows will have minimal impact and loss reduction is a co-objective. The results identified that savings are low, but reactive power support and voltage profile improvements are significant.

A.A.A. Esmin [10] et al. presented a hybrid particle swarm optimization technique (HPSO) for economical power flow operation. The HPSO technique is a population-based optimization technique that finds an optimal solution within a set of measures (limits). This iteration process identifies a set of critical buses first and then calculates the amount of shunt capacitors required to achieve maximum loss reduction in the system. A genetic algorithmic approach was used for testing sensitivity. For an IEEE 118 radial distribution bus system, using proposed techniques, a 1645.524 kW loss reduction was achieved, compared to a GA approach of 1109.772 kW. Since these two techniques use different optimization methods, the required shunt compensation varies between PSO (2.6671 pu) and GA (0.4157 pu).

M.H. Haque [11] presented a loss reduction technique using capacitor placement (single and multiple) for a radial distribution system. This technique identifies the optimum nodes for placing the capacitor(s) for achieving maximum loss savings. An iterative process is used and is repeated for all possible nodes in the system until it reaches a low loss value. The size of the capacitor is calculated based on the capacitor current requirement and a cost-benefit analysis. The proposed approach was tested on 15 bus and 33 bus radial distribution systems, and achieved 27.7 kW loss reduction (out of 61.8 kW) and 72.8 kW loss reduction (out of 369.3 kW) respectively.

J.A. Momoh [3] et al. presented a contingency-constrained optimal power flow program for the economical operation and planning of power systems. The proposed algorithm resolves the power flow contingency issues by checking bus voltage violation, VAr planning and finally, loss minimization. Once these preliminary checks are done, the economic dispatch is described based on the desired objective (either loss minimization or VAr requirements). This identifies the best economic dispatch to achieve the economical operation of the test system. A 118 bus partitioned interconnected system (radial distribution system) was used as the test system. As the primary objective, voltage violation buses were identified in each region (bus 13, 18, 19, 21, 22, 71, 75, 76 and 118). A new VAr site proposal (VAr planning) was tested iteratively on each location (for a total of eight locations) to identify the optimal location. Among all the possible locations, this technique identified that three locations (bus 13 (4.99 MVAr), 19 (32.35 MVAr) and 118 (102.70 MVAr) were ideal to limit voltage violations (improving the low voltage bus (0.8097 pu) to 0.9517 pu) and to achieve economic dispatch.

The next examples explain the use of a combination of techniques and different series power flow controllers to achieve loss minimization and economical operation. These series compensating devices use both series and shunt compensating devices.

S.A. Jumaat [12] et al. implemented particle swarm optimization (PSO) techniques to size and locate a thyristor controlled series compensated device (TCSC). The PSO technique identifies the line with the highest flow limit and maximum repair rate as an ideal location for loss minimization. Similarly, an evolutionary programming (EP) technique, i.e. an artificial neural intelligence based method, is used for sizing and locating the device. Since these two methods have different approaches, i.e. mutation for EP, and velocity and position approach for PSO, these techniques identify different compensation levels for the TCSC (based on load). PSO came up with an ideal loss reduction of 1754 kW (TCSC sized 0.3912 pu) compared to 1682 kW (TCSC sized 0.3213 pu) via the EP technique.

E.J.D Oliveira [13] et al. analyzed the influence of FACTS devices in a multi-period economic dispatch problem. A simple capacitor and phase shifters were placed using Benders' decomposition technique. This technique identifies lower and upper bound limits for the objective. The iteration process ends when the difference between upper and lower bounds is lower than a certain limit. The Brazil Southern Region Hydro units generation was limited due to a wheeling issue and resolved using the proposed technique. The losses increased from 90.5 to 104.3 MW due to generator re-dispatch imposed by the FACTS devices (more hydro generation). But the production cost was reduced (33 to 32.7 million dollars) in all cases.

M. Tripathy [14] et al. presented a bacterial foraging algorithm (BFA) to place FACTS devices to achieve maximum loss reduction. The algorithm mimics the foraging strategy, or the natural selection that eliminates the poor foraging strategy and either reshapes or favors only the successful foraging strategy, of bacteria (E. coli). This technique identifies the best or optimal location to place a UPFC, according to the amount of series voltage injected and the number of transformer taps in the test system. An interior point successive linear programming (IPSLP) method was used for comparison. This technique solves linear and non-linear constraints with inequality limits. The optimal solution was identified from the interior of the feasible region. The New England power system was used for this test purpose. The overall loss of 0.3900 pu (48.2 kW) was reduced to 0.2764 pu (34.16 kW) with the BFA technique, a greater value compared to the 0.3351 (41.414 kW) pu achieved by the IPSLP technique. The overall generation and loads were 6198.4 kW and 6150.5 kW respectively.

J.R. Shin [15] et al. implemented a new optimal routing algorithm called improved branch exchange (IBE) for minimizing the losses in a radial power system. The optimal routing algorithm is a multi-step iterative technique. For constructing a primary radial network, a genetic algorithm (to overcome the local optimum taps issue) is used, and later, a loss calculation index and voltage stability index are calculated to finalize the critical transmission path. This improves the voltage regulation and avoids the voltage instability issues with power flow changes. IEEE 32 and 69 bus test systems and the Korea Electric

Power Corporation (KEPCO) regional system were used as test systems. Compared to conventional branch exchange methods, IBE provided better loss reduction in all cases. In the case of the IEEE 32 bus system, loss reduction via both techniques was 135.549 kW. For the IEEE 69 and KEPCO 148 bus systems, the losses were reduced via the proposed approach to 99.62 kW (99.66 kW in the conventional method) and 916.94 kW (920.45 kW in the conventional method).

S.J. Lee [16] presented location selection criteria for superconducting devices using a loss sensitivity index. This index derives at each bus the sensitivity value of system losses with respect to increasing bus power. Based on this index, the superconducting device (Superconducting Magnetic Energy Storage (SMES)) is placed either as generator or load. A 5 bus test system was used for optimal location selection and system loss evaluation. Bus 4 (Troy), a major load center, was identified as an optimal location to place the device and achieved the better loss reduction of 0.1705 pu (1705 kW), compared to the system loss of 0.1913 pu (1913 kW) in the proposed test system. The overall generation in the test system was 344.1 MW.

G.K.V. Raju [17] et al. proposed and tested a sensitivity and heuristic-based multi-stage distribution (regional) system reconfiguration technique. This technique identifies the lines with low loss sensitivity indices. Then, by closing and opening the tie line switches, it identifies a suitable configuration that has minimum losses. During this process, multiple constraints like voltage and loading limits are also imposed in the path evaluation. Four test systems, IEEE 32, 69, 94 and 119 bus systems, were used for the evaluation of this technique. Losses of 139.55 kW, 30.12 kW, 471.44 kW and 891.88 kW were reduced to 139.55 kW, 30.09 kW, 469.87 kW and 870.35 kW with this technique. These are lower compared to other traditional techniques, which showed losses of 139.55 kW, 30.12 kW, 470.88 kW and 881.96 kW.

M.A. Syed [18] et al. proposed a control scheme for power loss minimization and voltage regulation on all nodes in a loop distribution system. An optimal node was identified based on a loop currents analysis to achieve loss minimization. Then, the FACTS device (UPFC) was used in voltage regulation mode to achieve voltage improvement. The optimal location and voltage reference limits were used in the control scheme to achieve minimum losses and increase the voltage regulation in the system. In the case of a radial system, similar voltage nodes were connected using loop wire, which converted it into a loop distribution system. An experimental test system (a four bus loop system) was used to test the control actions. The loss observed with the proposed technique in both radial and loop distribution systems was 191.2 kW (before, 193.7 kW) and 202.3 kW (before, 206.2 kW) respectively.

Again the majority of the results and references were based on distribution test systems. The transmission networks are more complex and are critical for determining optimal location selection. The research work carried out in this thesis will fill the gap in identifying and implementing FACTS devices and locations to achieve maximum loss reduction and improve the economical operation of the power system.

1.7 Motivation of Research

Conventional methods for device placement mainly concentrate on distribution networks for loss reduction. Unless required, these techniques ignore the device rating (as larger devices always cost more and are harder to replace) and use higher-rated devices to minimize the losses. Table 1.3 compares the average total cost (device, installation and testing) of several FACTS devices [19].

Individual device cost and other related financial issues must be compared, as device cost needs to be set as one of the primary objectives of the selection criteria. Another issue identified is the level of computation, as conventional techniques will identify and change locations iteratively. Along with these arguments, a new, advanced FACTS device, i.e. the Sen Transformer, is compared to the other devices and this will help the utilities evaluate its benefits. All these motivations served as a framework for carrying out this research work.

Table 1.3: Cost of different FACTS controllers (average)

FACTS controller name	**Cost (US $)**
Shunt capacitor	8/kVAr
Series capacitor	20/kVAr
PAR	15-20/kVAr
TCSC	40/kVAr
STATCOM	50/kVAr
SSSC	50/kVAr
UPFC	75-100/kVAr
Sen Transformer	15-20/kVAr

1.8 Objective of Research

The major objectives set in this research are as follows:

- Compare and quantify loss reduction with several FACTS devices.
- Compensate short transmission lines to achieve maximum benefits.
- Achieve economical operation with optimal placement of simple, low-rating devices.
- Resolve overloading issues among lines and achieve secure dispatch with redistribution.
- Resolve low voltage issues and maintain healthy bus voltage[1].

It is important to note that the objective is not a replacement technique for the existing optimal location selection criteria which does not take into whether the line that is to be compensated is long or short, but instead an enhancement that will ensure that short transmission lines are compensated first in the system.

[1]Voltagelimits :, Utility nominal voltages are ± 5 % (0.95 pu to 1.05 pu on the consumer end) and + 10% upper limit on transmission (0.95 pu to 1.1 pu on transmission line buses (to minimize losses, this varies by utility))).

1.9 Organization of the Thesis

With all these motivations and objectives, a proposed technique of short line compensation was implemented to minimize the losses. Simulation studies were carried out with different commercially available software packages , such as PSCAD/EMTDC, PSAT and PSS/E. These results were tabulated and compared to validate the proposed approach and quantify the economic benefits.

Chapter 1 has provided background on the importance of the economical operation of power systems along with the major inhibiting factor, transmission losses. A few other influencing factors such as voltage and line loading limits were briefly explained. Extensive research done on the implementation of power flow controllers (FACTS) for loss minimization was explained in the literature survey. A few other optimal location selection requirements and effects for economical operation were discussed.

Chapter 2 explains the requirements of power flow controllers for economical operation. Different kinds of FACTS devices such as simple capacitor devices, thyristor-based compensating devices and advanced Voltage Source Converters are explained in detail. The regulation techniques of these devices, their active and reactive power controlling and their voltage regulation are explained with formulae and appropriate phasor diagrams. Transformer-based FACTS devices (PAR transformers) are also explained. The operation and design of a low-cost and powerful regulator, the advanced Sen Transformer, and its usefulness for loss minimization, are explained in detail.

Chapter 3 deals with the implementation of FACTS devices in a real-time test system, i.e. a 12 bus system in a steady state condition. Different test environments such as PSCAD/EMTDC, PSAT and PSS/E are used to build and test for various operating scenarios. Line stability index calculations and comparisons are explained for optimal location selection. While choosing compensation levels, a set of levels are tested to identify optimal node points for achieving maximum loss reduction.

To validate the compensation levels, the overall system voltage profile is studied and sensitive voltage locations are identified. When considering line selection criteria, voltage profile improvement is also set as an objective and achieved with minimal effort. Other line overloading issues are also resolved by choosing an underutilized corridor for compensation. Due to design limits in PSS/E, the new, emerging FACTS device, the Sen Transformer (ST), is not tested in this software. Instead it is designed and tested in an electromagnetic transient environment (PSCAD/EMTDC).

Chapter 4 presents final conclusions on the capacity of current approaches to meet the main objective. Suggestions are made to alter the traditional validation approach and instead use the newly proposed approach discussed in this thesis. It also identifies transient stability issues for future study.

Chapter 2

Power Flow Controllers

2.1 Introduction

Chapter 1 explained the sources of losses, limiting factors for reducing line losses, as well the significant dollar savings that could be achieved even by reducing the losses by a small amount. This chapter introduces the different types of devices available that could be used to reduce the losses, help in improving the voltage profile in the system as well as reduce line congestion. Since transmission losses account for 5-10% of the generation of a power system, reduction is essential for economical operation. To reduce this loss, an easy technique available is optimal generation dispatch (with conventional, renewable and distributed generation). This technique is limited to the available generation capacity and load locations [20].

The other technique available is to control the power flow parameters (either impedance, voltage magnitude and phase angles) in the transmission line. To control these parameters, a special type of devices, i.e. a Flexible AC Transmission System (FACTS) devices, was used. These devices control the above parameters (one or more) and achieve maximum power flow (active, reactive and both) in the system. The other advantage is the reactive support provided to the system by these devices [21] [22] .

The evolution of FACTS devices started with a simple Fixed Series Capacitor (FSC) and Phase Angle Regulating Transformer (PAR). Control limitation in the FSC lead to the invention of thyristor-based devices, such as the Thyristor Controlled Series Capacitor (TCSC), Thyristor Switched Series Capacitor (TSSC), etc. [23]. Then, with the introduction of advanced power electronics (GTO,IGBT, MOSFET and anti-parallel diode etc), the advanced control capacity Static Series Synchronous Compensator (SSSC) and Unified Power Flow Controller (UPFC) were developed. These devices provide better regulation of transmitted power and support more economical operation [24] [25] [26].

The power electronic devices provide numerous benefits in the operation of power system, but the investment and operating costs of these devices could be very large. To limit these costs and achieve a similar transmission loss minimization, K. K. Sen introduced a transformer-based power flow controller, named the "Sen Transformer" (ST) [27] [28]. This device shares some common features with the PAR (phase angle control and voltage injection), and at the same time provides an independent active and reactive power control similar to that of the UPFC. It also contains a series and exciter (voltage regulating) unit similar to the PAR with a different design, i.e. the ST uses a single core while the PAR was designed with two transformer units [29].

A detailed working mechanism of each device (Fixed Series Capacitor, PAR and the FACTS Devices) is explained in the following sections.

2.2 Fixed Series Capacitor

A Fixed Series Capacitor is the most appropriate choice on the basis of cost (the costs are equal to approximately 10% of the total cost of the transmission line) and operation. This series connected capacitor regulate the line impedance and reduce the reactive power energy consumption. This allows more power to be transferred power in a compensated line and therefore the loop flow could be reduced through the longer segment of the interconnected network [11] [30]. The detailed operating principles and design of the FSC are explained in the following subsections.

2.2.1 Operating principle

Figure 2.1 explains the basic design of the FSC, i.e. capacitor banks and protective equipment like metal oxide varistor (MOV), a damping circuit, a spark gap, etc., in an aligned circuit. Again, the damping circuit consists of a parallel connected inductor (damping reactor) and resistor to protect the capacitor banks during power system oscillations. The ratings of the protective equipment largely depend on the peak currents during capacitor discharge.

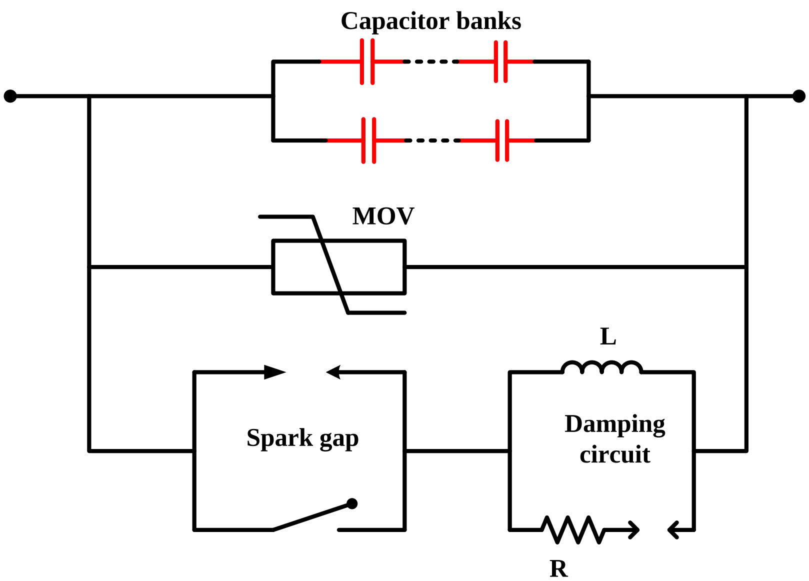


Figure 2.1: Fixed Series Capacitor block diagram

Equation 2.3 gives the voltage across the series capacitor produced by the series capacitance (X_C) and lagging currents injected into the system (i_c). This reduces the line impedance (X_L) into a new value (X_{new}) and transfer more power through the line. The phasor diagram of series compensation, Figure 2.5, shows the improvement in the receiving end voltage (V_R). The subsequent line voltage drop (V_X) was minimized by compensating voltage (V_C) supplied by the capacitor [30].

$$V_C(t) = -jX_c * \int i_c(t)dt \tag{2.1}$$

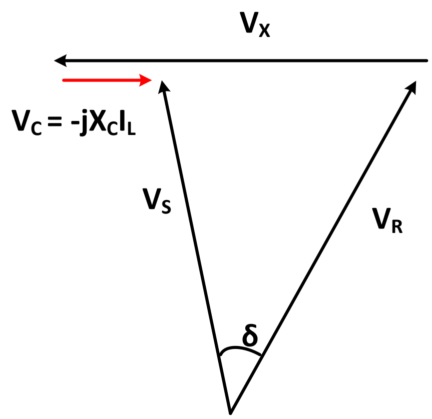


Figure 2.2: Phasor diagram of fixed series compensation

$$i_c(t) = I_L * cos(\omega t) \tag{2.2}$$

The reactive power (Q_C) supplied by capacitor banks with level of compensation 'k' is,

$$Q_C = \frac{2V_SV_R}{X_L}\frac{k}{(1-k)^2}(1-cos\delta) \tag{2.3}$$

Equations 2.4 and 2.5 give the incremented new active and reactive power in a simple two area system.

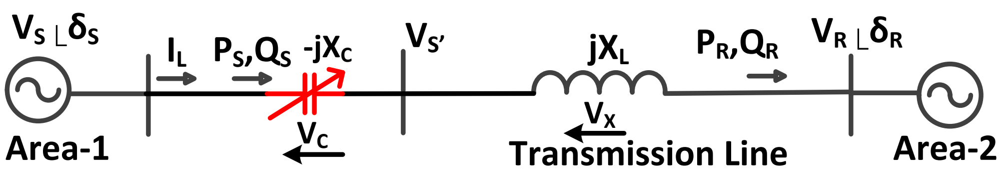


Figure 2.3: Fixed Series Capacitor compensation in two area system

$$P_R = \frac{V_SV_R}{(X_L - X_C)}sin\delta \tag{2.4}$$

$$Q_R = \frac{V_SV_R}{(X_L - X_C)}(1-cos\delta) \tag{2.5}$$

The resultant reactive power produced by the capacitor banks will vary with incremental loads and acts as a self-regulating device. Under operating limits, series capacitors are more reliable, accurate and instantaneous compared to other devices.

The major limiting factor in FSC compensation is the degree of compensation (k). Equation 2.6 gives the expression for k:

$$k = \frac{X_C}{X_L} \tag{2.6}$$

In general, for power transmission applications, the maximum allowable degree of compensation will be in the range of 0.3 $\leq$ k $\leq$ 0.8 [21]. Exceeding this limit will cause over-voltage on load side during light load conditions (damages the transformers and capacitors), could cause ferro-resonance [31], and result in increased fault current levels. To avoid these issues, an ideal compensation value between the allowable limits is used.

2.2.2 Design of the FSC

The FSC shown in Figure 2.1 was modeled in PSS/E. It can be seen from the figure that the modeling of this device is quite straightforward. A simple capacitor bank (0.24419 μf and 0.46456 μf) are used to build 250 MVAr and 57 MVAr FSC devices. The cost of design, construction and installation are discussed in later chapters.

2.3 Phase Angle Regulating (PAR) Transformer

A Phase Angle Regulating Transformer is the only device that can control both power flow and magnitude. With its low maintenance cost, the PAR is the most popular electro-magnetic power flow controller among the complex electronic FACTS devices [32].

2.3.1 Operating principle

At first, to find the required rating of the device, Equation 2.7 was derived from simple factors like the line MVA rating and the required positive or negative phase shift (θ).

$$\text{PAR Transformer rating (MVA)} = 2 * LineMVA * sin(\frac{\theta}{2}) \tag{2.7}$$

As shown in power flow Equation 2.8, the power transfer is a function of the system voltages' magnitude (V_S, V_R) and phase angles (δ) with line impedance (X_L) as constant. Varying the voltage phase angle will stipulate the MVA loading of the line. So, the power flow will be easily regulated by the sin δ function, i.e. the required phase shift of the transformer.

$$P = \frac{V_S V_R}{X_L} sin\delta \tag{2.8}$$

The basic design of the PAR transformer has been explained by multiple authors [32] [33] [34] and typically consists of two interconnected transformers controlled by load tap changers. Figure 2.4 shows the interconnected transformers that are sub divided into two units, i.e. series and exciter units. Connecting the series transformer unit to the line results in high series impedance, which will increase the leakage reactance. The exciter unit regulates the series impedance by using tap changers, and injects quadrature voltage as required.

In detail, when nominal voltage (V_S) is applied to the primary transformer, an induced exciter voltage (V_q) will be generated and injected in quadrature (90 degrees) with the line-to-neutral voltage of the series unit. Equation 2.9 explains the relation between the phase voltage (V_{L-N}) and the injected phase voltage (V_q). The phasor diagram shown in Figure 2.5 explains all three phase operating regions of the injected voltage phase shift (V_q) and the resultant voltage at the secondary transformer ($V_{S'}$). Equation 2.10 derives the net phase shift (θ) achieved; the value will be either positive or negative depending on the sending end (V_S) and receiving end (V_R) voltages.

$$V_q = (V_{L-N})(2sin\frac{\theta}{2}) \tag{2.9}$$

$$\theta \cong tan(\theta) = \frac{V_R}{V_S} \tag{2.10}$$

Although it has multiple advantages, its slow operating speed is one of the major issues with the usage of a PAR transformer. This can be resolved by speeding tap changers up to a certain extent. Another major limiting factor is the introduction of high series impedance to the compensated line. At high power transfer levels, the PAR will consume a significant amount of reactive power, so a large reactive power source is mandatory to ensure voltage

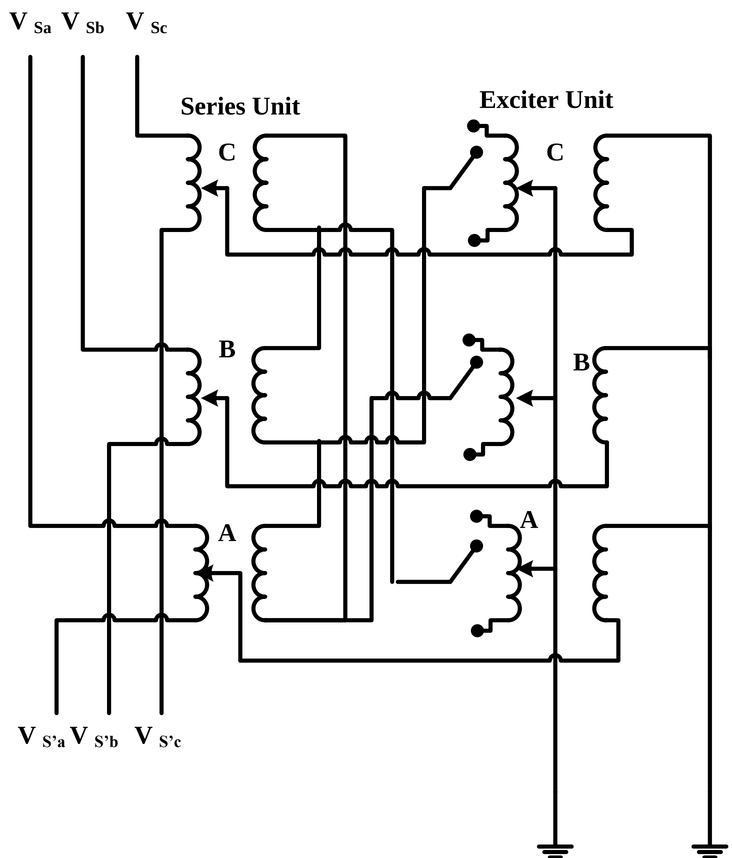


Figure 2.4: Phase Angle Regulating Transformer

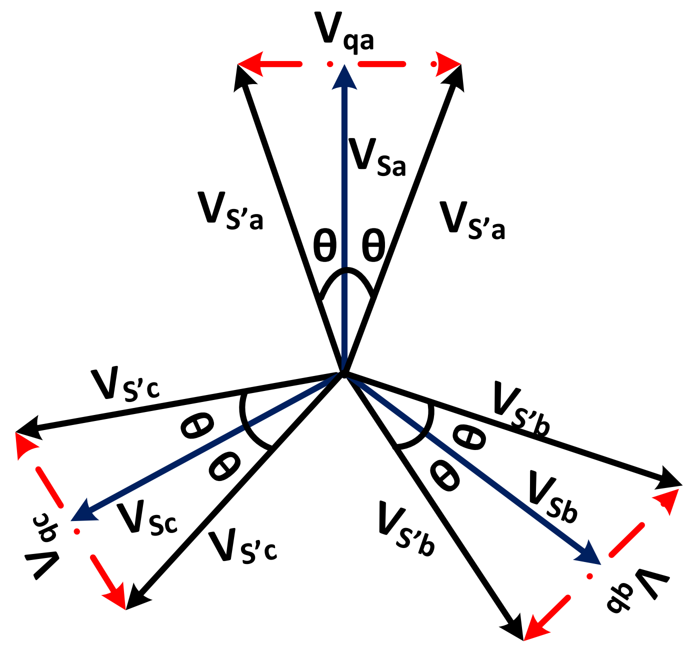


Figure 2.5: Phasor diagram

regulation at that location. Another design and operating issue is the quadrature limit of the injected voltages; the other electronic-based FACTS devices are capable of a wider range of injected voltage.

2.3.2 Design of the PAR transformer

The PAR transformer was built in PSS/E using conventional transformer and tap changers. Two series units (120 MVA, 345/345 kV, Z =0.5 % and 35 MVA, 230/230 kV, Z =0.5 %) are used to build a PAR transformer. Furthermore, the series and exciter units are modeled as delta-delta and wye-wye configurations. The resultant PAR transformer ratings are 250 MVA and 130 MVA respectively. The designed transformers are capable of producing $\pm$ 15° in voltage phase shift.

2.4 Thyristor Controlled Series Capacitor (TCSC)

The introduction of series compensation on a transmission line raises some operating issues such as subsynchronous resonance, loop flows in parrelel transmission lines and transient recovery voltage etc. during power system oscillations. To address these issues and control the cap-bank capacity instantly, a new power electronics technology for industrial applications, was introduced around 1980. The primary focus of these devices (Static VAr Compensators (SVS)) is power factor correction and reactive power support. In addition, in 1990 EPRI (USA) proposed an advanced power electronics FACTS device called the Thyristor Controlled Series Capacitor (TCSC) for industrial application [21].

Since then, thyristor-based devices have become the most commonly used power flow controllers after the fixed series capacitor. Improvements in thyristor technology (high current and high voltage operations) have turned them into multi-purpose devices, allowing them to control series compensation with damping oscillations and to mitigate resonance issues. The major thyristor-based devices used for power regulation are:

1. **Thyristor Switched Series Capacitor (TSSC)**

A TSSC is designed with a series capacitor bank controlled by a thyristor via stepwise controlled series inductance. In this, there is no firing angle control, and the firing angles fed to the thyristor bank are either 90° or 180°. This will switch the series inductance in or out and control the capacitance based on the requirements, thus costing less.

2. **Thyristor Controlled Series Capacitor (TCSC)**

The TCSC model contains firing angle control and operates dynamically. Though the cost of the TCSC is high compared to the TSSC, it has been extensively used for its smoother operation of thyristor controlled reactors than other switched reactor technologies. Figure 2.6 shows the control of a series capacitor by a variable impedance thyristor bank controller.

This offers powerful controlling factor and increases power transfer capability to the

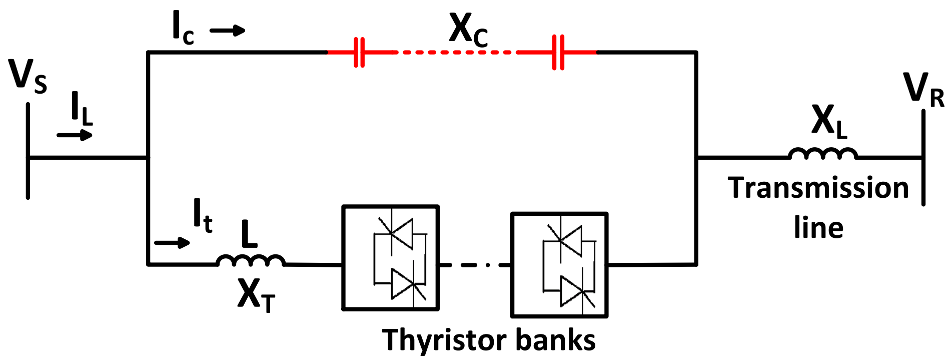


Figure 2.6: A simple TCSC structure

transmission line. Along with its primary components, a MOV and a bypass breaker are added in industrial applications. These will protect the series capacitor banks from transient and short circuit conditions.

2.4.1 Operating principle

Equation 2.11 calculates the required amount of the capacitor for the proposed line of compensation. Based on this maximum series capacitance, Equations 2.13 and 2.12 determine the appropriate capacitive (X_C) and inductive (X_T) reactance for design of the TCSC. The firing angle fed to the thyristor bank determine the net reactance injected into the system. Equation 2.14 determine the change in net reactance (X_{net}) with respect to the firing angle fed to the thyristor banks.

$$C_T = \frac{1}{(2\pi * f * X_C)} \tag{2.11}$$

$$X_T(\alpha) = X_L \frac{\pi}{(\pi - 2\alpha - Sin2\alpha)} \tag{2.12}$$

$$X_C = \frac{1}{2\pi * f * C} \tag{2.13}$$

$$X_{net}(\alpha) = \{-X_C + (\frac{X_C + X_{LC}}{\pi})(2(\pi-\alpha) + sin(2(\pi-\alpha))) - \frac{4 * X_{LC}^2}{X_T * \pi} cos^2(\pi-\alpha)(\omega tan(\omega(\pi-\alpha)) - tan(\pi-\alpha))\} \tag{2.14}$$

here,

$$X_{LC} = \frac{X_C X_T}{X_C - X_T} \tag{2.15}$$

$$\omega = \sqrt{\frac{X_C}{X_T}} \tag{2.16}$$

If the firing angle fed to the thyristor (α) ranges from 0° to 90°, each degree will affect bringing the actual transmission line impedance (X_L) to a new value. The inductive mode of operation lies between 0° to 49° and the capacitive mode, between 69° to 90°. If the firing angle varies from 0° to 49°, the TCSC inductive reactance varies from X_L to infinity. Similarly, if the firing angle operates between 69° to 90°, the resultant capacitance injected into the line will vary from X_{Cmin} to X_{Cmax}. Due to the possibility of resonance, the operating range between 49° to 69° has been strictly prohibited [35].

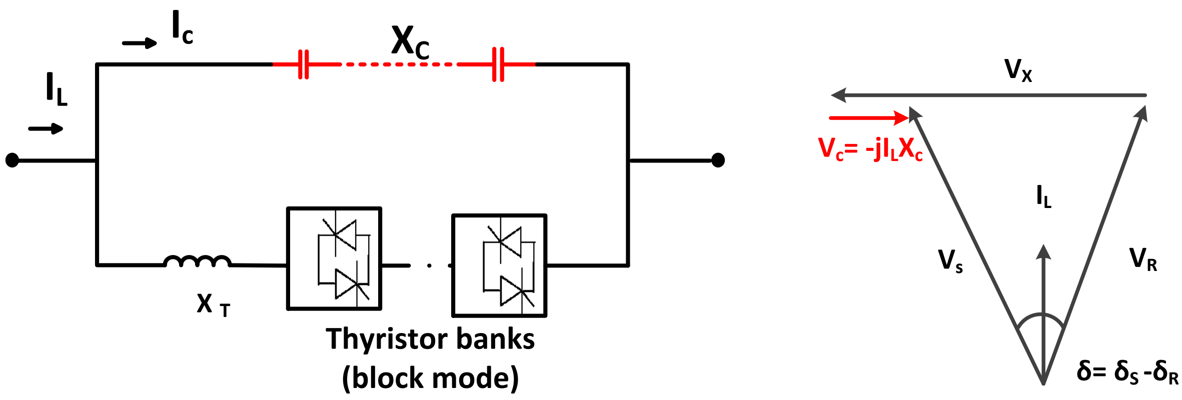
The thyristor operation in the TCSC are classified into block and unblock modes. During block mode, the TCSC acts as a pure capacitor that provides series compensation similar to the FSC. Figure 2.7 explains the flow of current, the appropriate phasor injected voltages (V_C) in the system and the resultant receiving end voltage (V_R). Similarly, Figure 2.8 explains the unblock (inductive) mode of operation of the TCSC and its appropriate phasor diagram.

The maximum net reactances (X_{net}) for the TCSC block and unblock modes are explained below.

If **$\mathbf{X}_{net}$ =+1.0 pu** (operating with no thyristor current - block mode);

$\mathbf{X}_{net}$=+1.5 pu (operating with thyristor firing such that the 60 Hz component of the capacitor voltage is $1.5 * X_c * I_{line}$ and lags current by 90° [capacitor] - unblock mode)

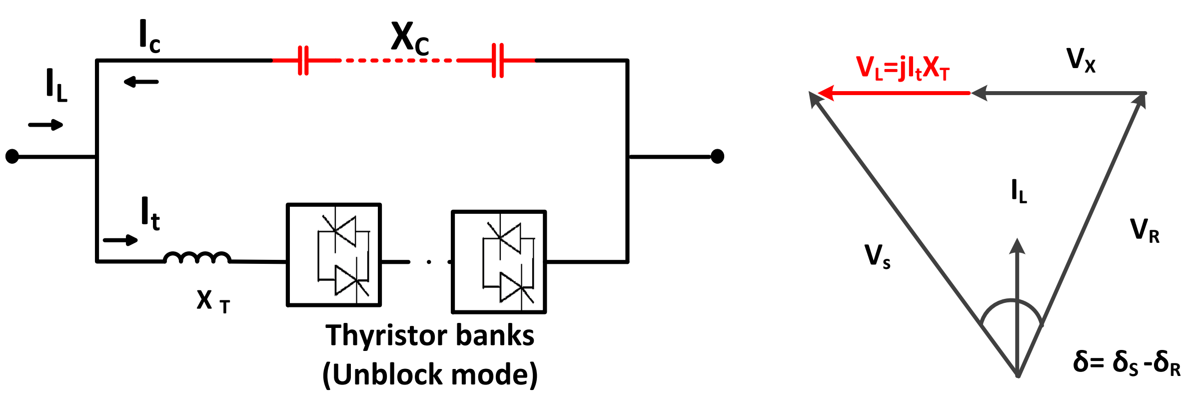
$\mathbf{X}_{net}$=-0.5 pu (operating with thyristor firing such that the 60 Hz component of the capacitor voltage is $0.5 * X_c * I_{line}$ and leads current by 90° [Inductive] - unblock mode)



(a) TCSC thrystor in block mode

(b) Phasor diagram

Figure 2.7: TCSC capacitive mode with phasor diagram



(a) TCSC thrystor in unblock mode

(b) Phasor diagram

Figure 2.8: TCSC inductive mode with phasor diagram

2.4.2 Design of the TCSC

The design of the TCSC in PSS/E is quite straightforward and similar to the FSC except for the thyristor banks. The required reactance rating in the TCSC is lower compared to capacitor bank rating (5-20%) and provide more control on reactive power support to the system. The following Table 2.1, explains the design ratings of the components to achieve compensation similar to that of the FSC [36].

Table 2.1: TCSC design rating

Component name	**230 kV line**	**345 kV line**
Capacitor	55 Ω	35 Ω
Inductor	15 Ω	5 Ω
Degree of compensation	70-100%	5-35%
Thyristor data	100 mm, 3.5 kA (continuous), 5.5 kV	100 mm, 2.0 kA (continuous), 10 kV
Reactive power	165 MVAr	350 MVAr

Based on the required compensation (active and reactive power flows), the firing angle was calculated for Equation 2.14. The control of these firing angles in PSS/E was designed using firing angle controller. In this a capacitor voltage (magnitude) will be compared with reference voltage and difference will be feed to a PI controller to caluculate firing angle. Another control loop of line currents (each phase) will be feed to phase lock loop (PLL) to produce a PLL reference angle (negative) will be summed with PI controller reference angle and feed to back-to-back thyristors to achieve the required compensation.

2.5 Voltage Source Converter

Advancement in thyristor technology has provided high speed switching, gate on and off control and higher power-rated transistors. This has introduced new, self-commutated converters to line compensation technology. These devices provide high power quality and minimal switching impacts. Another advantage of these technology is its external power support to weak interconnected system [37]. There are two basic configurations available to build the required advanced FACTS devices. One is the Current Source Converter (CSC) and the other is the Voltage Source Converter (VSC).

Between the two, the VSC is the most effective in an AC system with its added flexibility of secure commutation. The features of the VSC are a combination of those of an SVC and a conventional current source converter. The basic design of the VSC is based on self-commutating switches (high voltage GTO (gate turn off thyristor) and IGBT valves) which will turn on or off instantly. This device uses various pulse width modulation techniques for inverter mode operation to provide near AC sinusoidal voltage. Figure 2.9 shows the PWM reference signal used to generate the sinusoidal voltage signal.

During this, commutation on a force-commutated VSC valve occurs multiple times per cycle and generate a sinusoidal wave. Figure 2.10 explains the operation of a single leg set of thyristors to generate the injected voltage.

Figure 2.11 explains the basic design of the VSC, which is a combination of thyristors, diodes and a capacitor. The DC capacitor provides the stiff DC voltage required to generate the voltage and virtually split it into two halves, $+V_0/2$ and $-V_0/2$. By adding a number of multi-phase legs in parallel using a transformer, it generates a low harmonics content and a near sinusoidal waveform.

A continuous and sequential switching operation using a pulse width modulator generate a near sinusoidal AC voltage waveform from the VSC. The switching operation can be altered or controlled and achieved through firing pulses that are fed to the GTOs. With reference to the phase angles, the generated voltage phase angle transfer or inject real power in the leading condition and draw real power in the lagging condition. In the case of a reactive power scenario, the voltage magnitudes (V_{inj}) (refer to Equation 2.17) play the key role. Reactive power is injected into the system when the generated voltage magnitude is greater than the system voltage, and vice versa.

$$V_{inj} = mV_0Sin(2\pi f_{ref}t + \theta_{ref}) \tag{2.17}$$

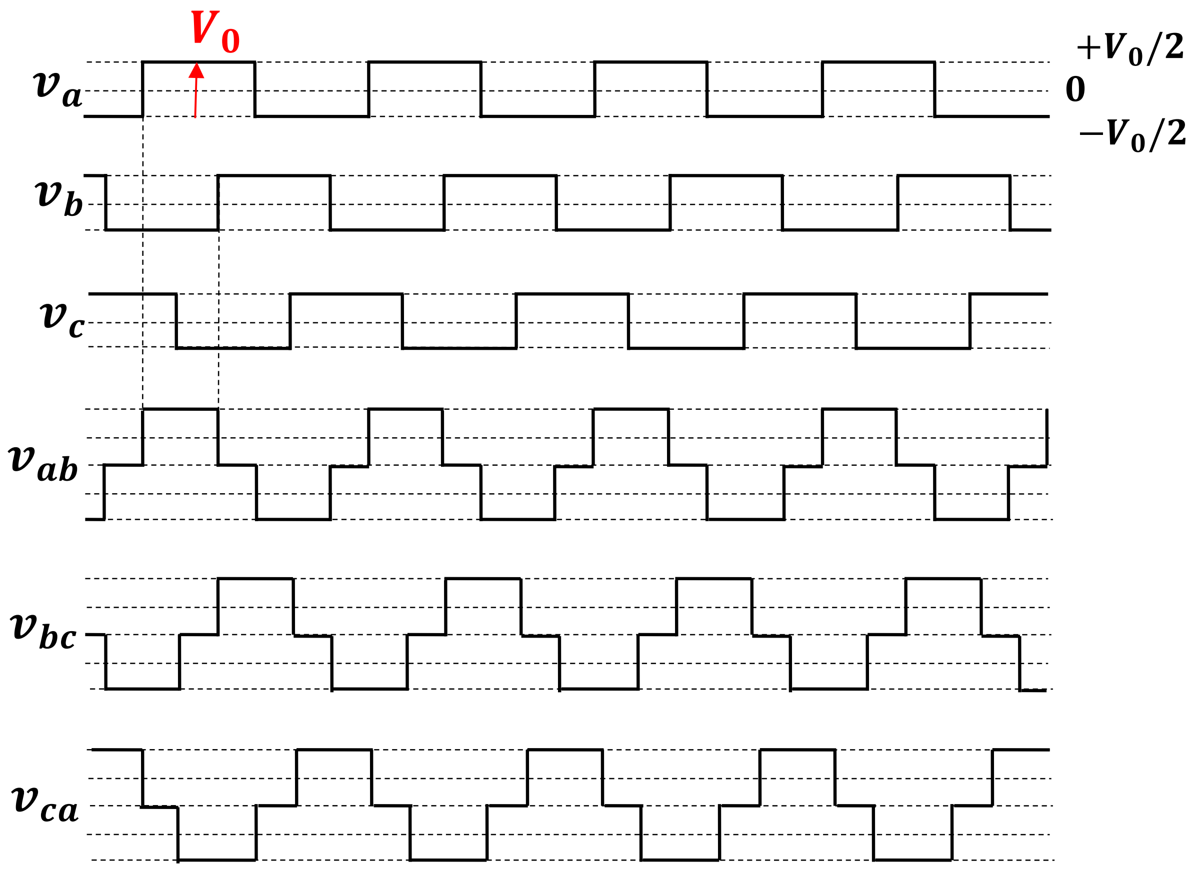


Figure 2.9: PWM reference signal

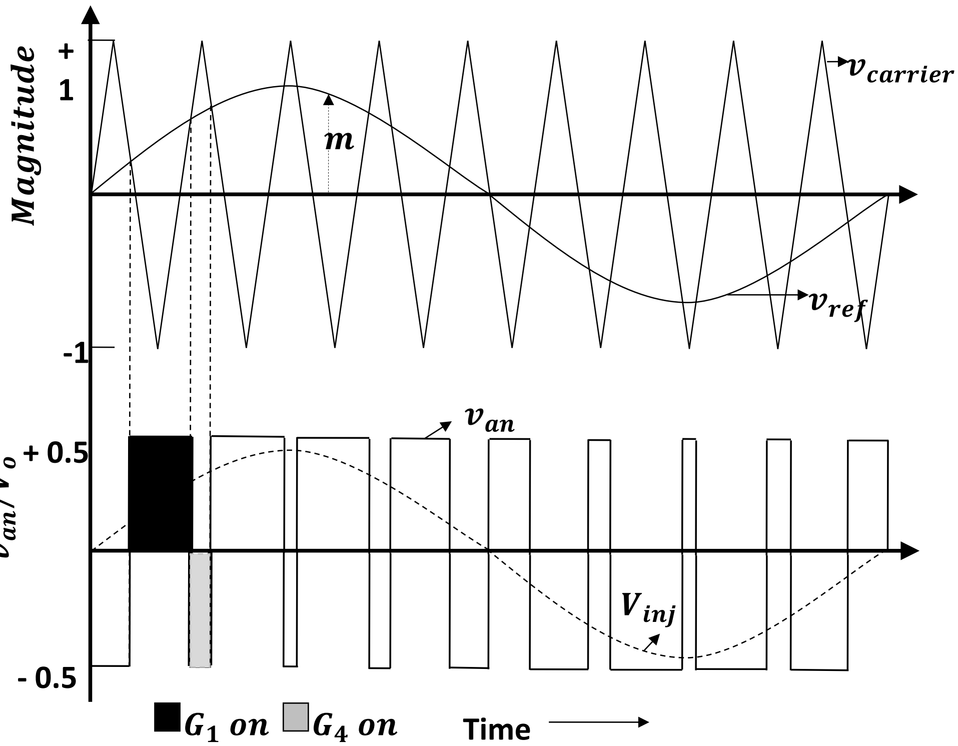


Figure 2.10: PWM output for single leg operation

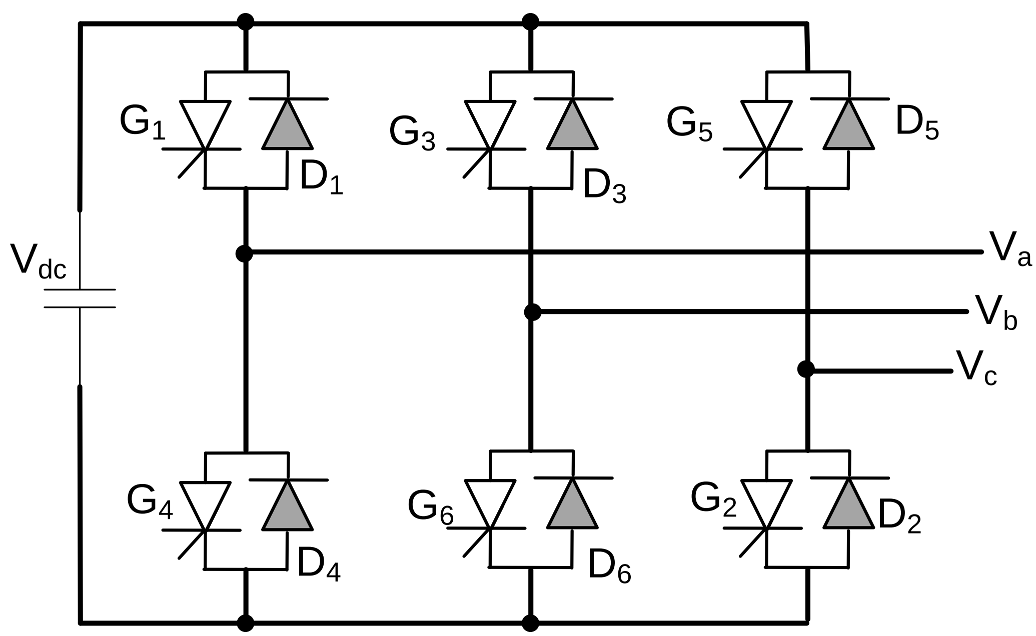


Figure 2.11: Voltage source converter

Where

$$m = \frac{\text{peak amplitude of reference signal}}{\text{pealk amplitude of carrier signal}} = \frac{v_{ref}}{v_{carrier}} \tag{2.18}$$

$$\theta_{ref} = \theta_{sync} + \delta_{converter} \tag{2.19}$$

Here V_0 is the input DC link capacitor voltage to the converter, f_{ref} is the reference frequency signal (60 Hz) and θ_{ref} is the sum of the phase angle of the reference signal (θ_{sync}) (which is phase synchronized to the system) and the phase angle ($\delta_{converter}$) obtained by the converter control system.

When the sinusoidal PWM technique is applied to trigger the GTO to turn on and off, a sinusoidal signal V_r with amplitude A_r will be generated with reference to the sawtooth waveform of V_s with amplitude A_s. The frequency of the sawtooth waveform will be based on the frequency of switching the GTOs. When $V_r > V_s$, this is the turn on signal for block one and the gate turn off signal for block two, and vice versa.

2.6 Static Synchronous Series Compensator (SSSC)

A Static Synchronous Series Compensator (SSSC) is a type of series compensating device (using VSC), a solid state voltage source inverter-based FACTS device. The operation of an SSSC is basically that of a VSC injecting a controllable independent (nearly sinusoidal) AC sinusoidal voltage (both magnitude and phase angle independent) into a transmission system in series to exchange active or reactive power in the system. This exchange is done in three phases of the transmission line, using a coupling transformer as shown in Figure 2.12.

The SSSC can be operated as an impedance compensation controller by adding an energy source, which will provide the required compensation for line reactance. By connecting a DC capacitor, a similar SSSC device can operate as a reactance compensation controller. The capacity of the DC capacitor bank will determine the maximum possible installation capacity of the SSSC device (for n phases) in the proposed transmission line. Equation 2.20 refers to the maximum capacitor bank capacity based on the injected voltage (V_{injmax}), maximum

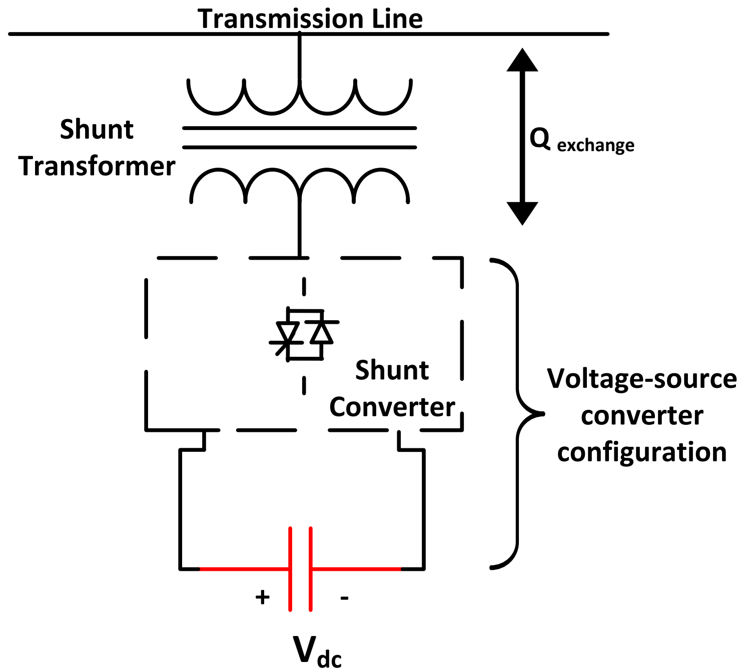


Figure 2.12: Basic configuration of SSSC device

line current(I_{max}) and number of capacitor banks (n).

$$CapacitorBank_{max} = \sqrt{3}.V_{injmax}.n.I_{max} \tag{2.20}$$

2.6.1 Operating principle

The inductive or capacitive compensation (X_q) introduced by an SSSC adds or modifies the transmission line reactance (X_L). This reduces the overall line impedance (X_L) to a new value (X_{comp}) as shown in Figure 2.13. Figure 2.14 shows a normal, series inductive

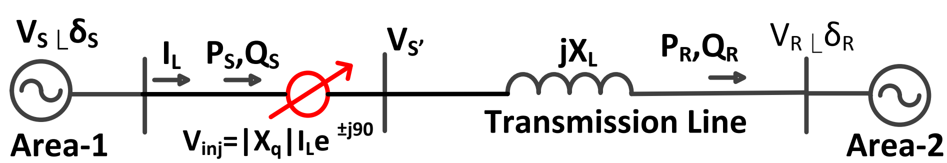
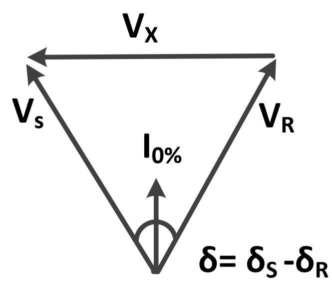
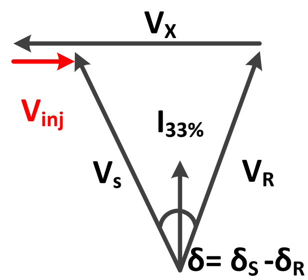


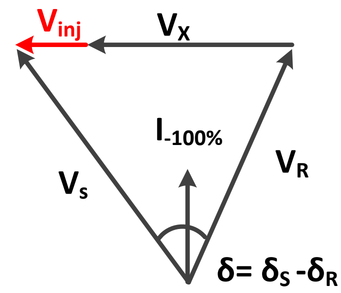
Figure 2.13: SSSC device in voltage injection mode



(a) Normal mode



(b) Capacitance mode



(c) Inductive mode

Figure 2.14: Phasor diagram of SSSC on multiple modes

or capacitive compensated voltage (V_q) and the resultant voltage drop (V_X) that occurs in the system. The injected AC voltage (V_q) also contains a small portion of voltage that is in phase with the line currents, which causes some power loss in the converter. The capability of the SSSC to change the injected voltage instantly, will dynamically influence the power flow in the transmission line [38]. The dynamic configuration of the SSSC and its injected voltage modes are shown in Figure 2.16.

As discussed above, adding an energy source (operating in an impedance controller) helps to control both the active and reactive power transmitting through the line. To achieve the maximum power flow, the injected voltage always lags the line current, which will increase the level of compensation in the transmission line (capacitive mode). On the other hand, to decrease the power flow, the injected voltage leads the line current, which will decrease the level of compensation in the transmission line (inductive mode). Equations 2.21 and 2.22 determine the receiving end power determined by SSSC reactive compensation (X_q).

$$P_R = \frac{V_s V_R}{X_L(1 - \frac{X_q}{X_L})}(Sin\delta) \tag{2.21}$$

$$Q_R = \frac{V_s V_R}{X_L(1 - \frac{X_q}{X_L})}(1 - Cos\delta) \tag{2.22}$$

Figure 2.15 explains relation between mode of operation and resultant sending and receiving end powers with level of compensation. Figure 2.16 shows the maximum power transfer

(1.5 pu), that can flow with maximum injected voltage (0.707 pu).

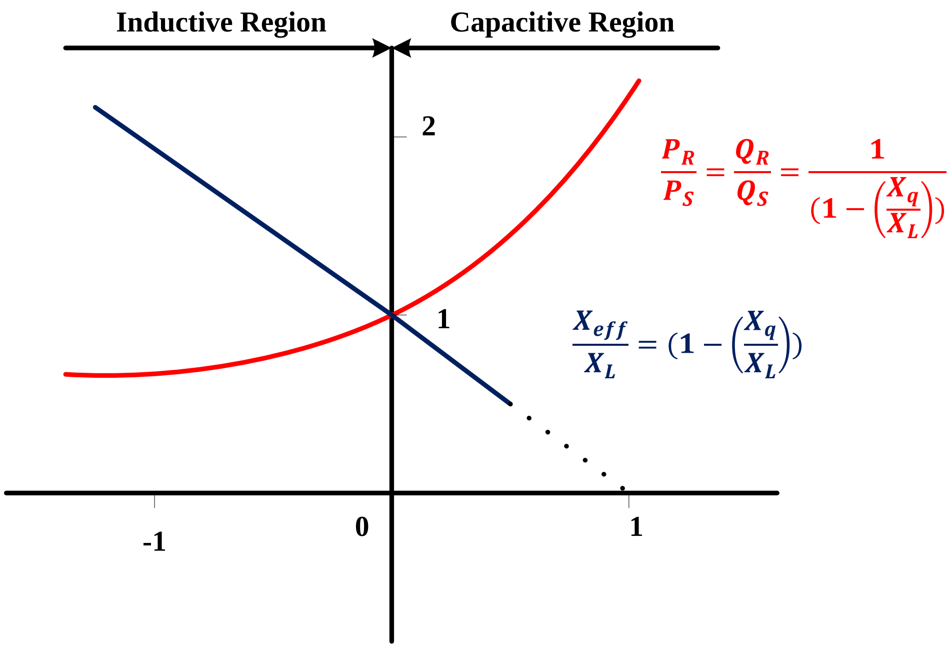


Figure 2.15: SSSC mode of operation

The limiting factors for voltage injection are voltage, stability and the thermal limits of the conductor.

2.6.2 Design of the SSSC

The design of an SSSC depends solely on the construction mechanism of the Voltage Source Converter and its DC capacitor limit. A 6 pulse VSC was used to design the SSSC for compensation. The series transformer was also rated based on the level of compensation and associated line ratings (150 MVA transformer (500 MVA line), 40 MVA transformer (250 MVA line)). Again, similar to the TCSC, the firing angle fed to the thyristor banks is designed with PSS/E component blocks and derived based on the level of compensation (voltage injection) requested.

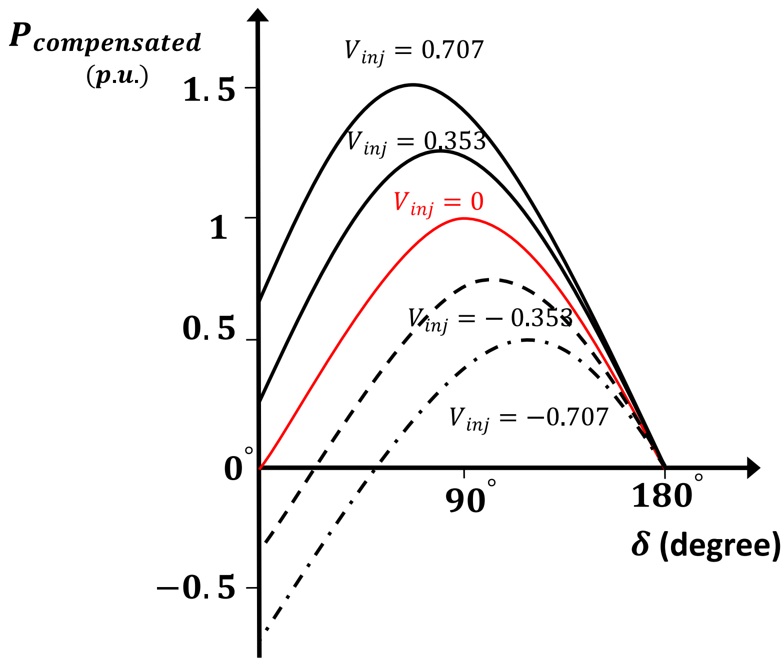


Figure 2.16: Relation between the phase difference and receiving end power in SSSC

2.7 Unified Power Flow Controllers

The Unified power flow controller (UPFC) is a combination of series and shunt voltage source converters sharing a common DC capacitor bank in the middle. In detail, it can be classified into two units. The primary unit is a shunt connected transformer attached to VSC on primary side where capacitor bank on secondary, also called as Static Compensator (STATCOM). The other second unit is a series connected VSC with a transformer connected in parallel to transmission line, also called as an SSSC. These two units provide conventional control capabilities in power flow and simultaneously satisfy the power flow regulation requirements.

The major control techniques are as follows:

1. Reactive shunt compensation or bus voltage regulation;
2. Reactive series compensation or line impedance compensation.

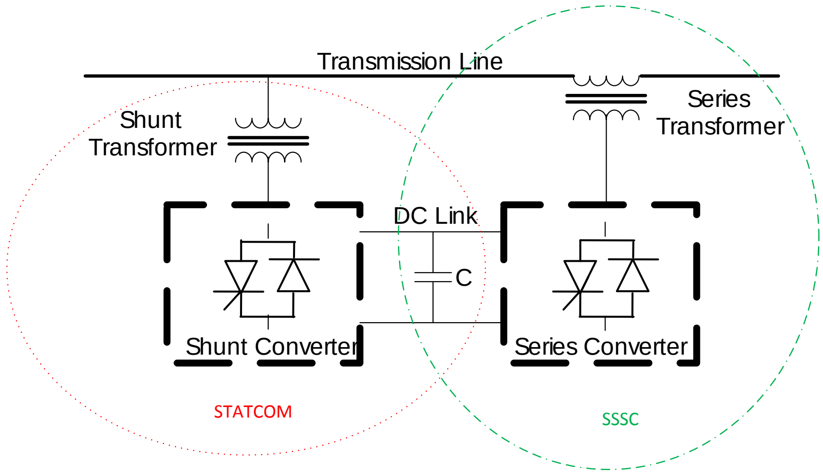


Figure 2.17: UPFC block diagram

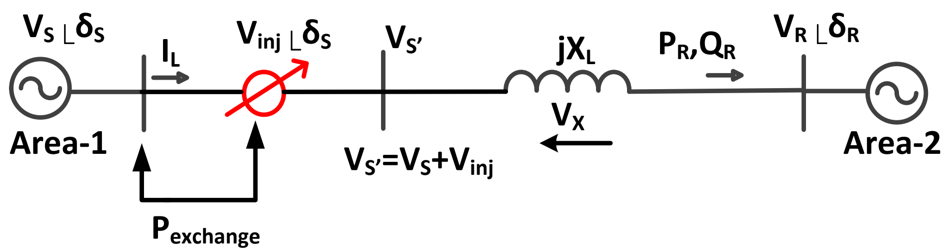


Figure 2.18: UPFC voltage injection

Between them, the UPFC achieves shunt voltage regulation by injecting an in-phase or anti-phase voltage varying within the maximum and minimum injection limits. These limits are controlled by the ratings of the shunt converter.

2.7.1 Operating principle

The series converter can inject a voltage, (V_{ser}) in quadrature with the line current (I_{line}), representing an inductive or a capacitive compensation. The range of the series voltage injection is generally independent of the line current variation and its limits depend solely on the converter ratings. Phase angle regulation injects ($V\angle\theta$) angularly with respect to the reference phasor, by advancing or oppositely moving it at an angle θ while keeping its

magnitude constant. The multifunctional control ability achieved by the UPFC is described wherein the UPFC simultaneously controls the bus voltage, line compensation (capacitive) and phase angle regulation by injecting a net voltage V_{inj} that can be derived as
In the case of the SSSC,

$$V_{inj} = -jX_c I_{line} \tag{2.23}$$

In the case of the STATCOM, the reactive power absorbed or injected will be:

$$I_{STATCOM} = \frac{(V_{sys} - V_{conv})}{X_{line}} \tag{2.24}$$

$$Q = \frac{(1 - \frac{V_{conv}}{V_{sys}})}{X_{line}} V_{sys}^2 \tag{2.25}$$

The ultimate combination of the equipment, means the UPFC's injected voltage will be:

$$V_{inj} = V_{shunt} + V_{series} + V_{\phi} \tag{2.26}$$

$$V_{inj} = |V_{inj}| e^{j(\frac{\delta}{2} + \phi)} \tag{2.27}$$

The respective active and reactive power values will be,

$$P_R = P_0(\delta) + P_{inj}(\phi) \tag{2.28}$$

$$P_R = \frac{V^2}{X_{line}} sin\delta - \frac{VV_{inj}}{X_{line}} cos(\frac{\delta}{2} + \phi) \tag{2.29}$$

$$Q_R = Q_0(\delta) + Q_{inj}(\phi) \tag{2.30}$$

$$Q_R = \frac{V^2}{X_{line}}(1 - cos\delta) - \frac{VV_{inj}}{X_{line}} sin(\frac{\delta}{2} + \phi) \tag{2.31}$$

Along with the injected voltage, the phase angle also affects the transfer power. In general this angle can vary between 0° and 360°. As shown in Figure 2.19, UPFC inject or absorb maximum active power on 0° and 180° and maximum reactive power on 270° and 90° respectively . Similarly operating between these limits will either abosorb or inject power (both) instantly. For example the operating region in between 0° and 90° real power injection will go from maximum to zero and reactive power absorption will be zero to maximum. A detailed explanation of the phase angle effect on the transmitted power is shown in Figure 2.19. In addition to active and reactive power support, UPFC also improves transient stability and helps in damping power system oscillations. Transient stability is the not focus of this research work so this benefit is not further discussed in this thesis.

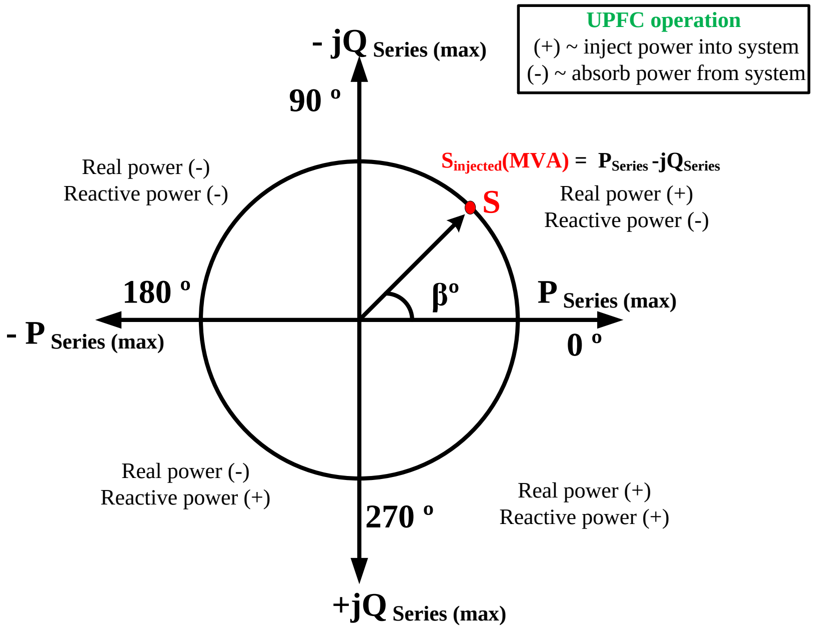


Figure 2.19: UPFC injected voltage phase angle effect on transmission line

2.7.2 Design of UPFC

As discussed in the operation subsection, a UPFC designed with PSS/E is a combination of two well-known FACTS devices, the STATCOM and the SSSC. The individual design of these components is done through 2 X 6 pulse voltage source converters, 2 transformers and a DC capacitor. The rating of these compensators is based on the level of compensation and the line MVA rating (a 150 MVA UPFC for a 345 kV line and a 40 MVA UPFC for a 230 kV line). Equation 2.25 derives the level of compensation (voltage injected) required to achieve maximum power flow. Similar to all other designed VSCs, the firing angles fed to the VSC thyristor banks are designed with PSS/E components and are applied based on the required voltage injection (carrier reference signal).

2.8 Sen Transformer

In 2003, Sen introduced the Sen Transformer, a device that functions similarly to the UPFC at a lower cost (it is claimed in the publihsed works that it would $\frac{1}{5}^{th}$ of the total UPFC cost) [27]. This device functions on transformer-based tap changer technology and provides independent active and reactive power control like a UPFC. The basic design of the Sen Transformer looks like a three phase transformer, with multiple (two to three) secondary windings per phase uniquely coupled with the primary. For control operation, the secondary windings are designed with on-load tap changers. Figure 2.23 shows a single phase complex structure (phase A) of a Sen Transformer. The other two phases are connected in similar fashion and are controlled by load tap-changers.

2.8.1 Operating principle

Figure 2.21 explains the Sen Transformer's basic power flow exchange during transmission line compensation. Here, the control of active and reactive power is done through series and quadrature voltages (V_d and V_q) injected into the system. Hence the on-load tap changers will operate in 1-2 cycles and regulate the injected voltage magnitude (V_{ser}) and phase angle (β). The receiving end voltage (V_R) is the combination, or the resultant voltage, of the system voltage (V_S) and the injected voltage (V_{ser}).

The Sen Transformer's injected voltage phase angle (β) can be varied from 0° to 360° and depends on the level of compensation required. To limit the cost, a limited angle operated Sen Transformer was introduced [27] [34]. For this, a design modification (a single winding in the secondary multi windings is removed) is deployed. This limits the injected phase angle to 120° operating region blocks (such as 0° to 120°; 120° to 240°, 240° to 360° etc.).

The phasor diagram in Figure 2.22 explains the relation between the series injected voltage and the receiving end voltage. Except with a limited angle operated Sen Transformer, a complete 360° operation will result in lead or lag injected voltage into the system and consequently control the power flow.

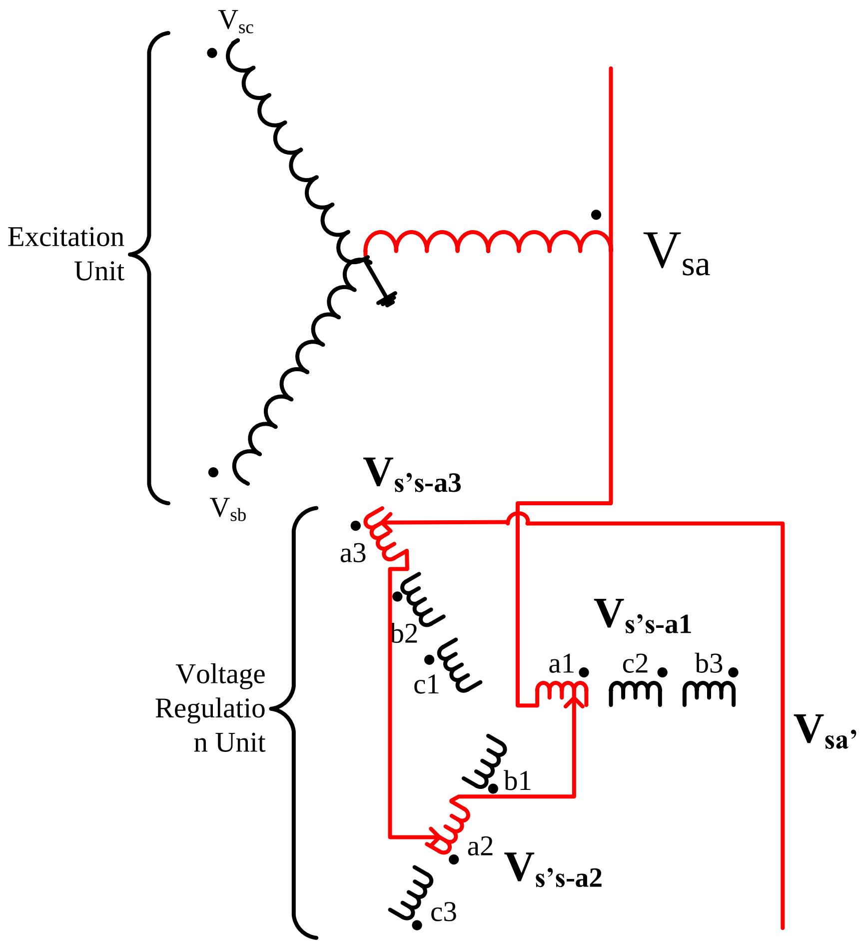


Figure 2.20: Sen Transformer phase-A connection

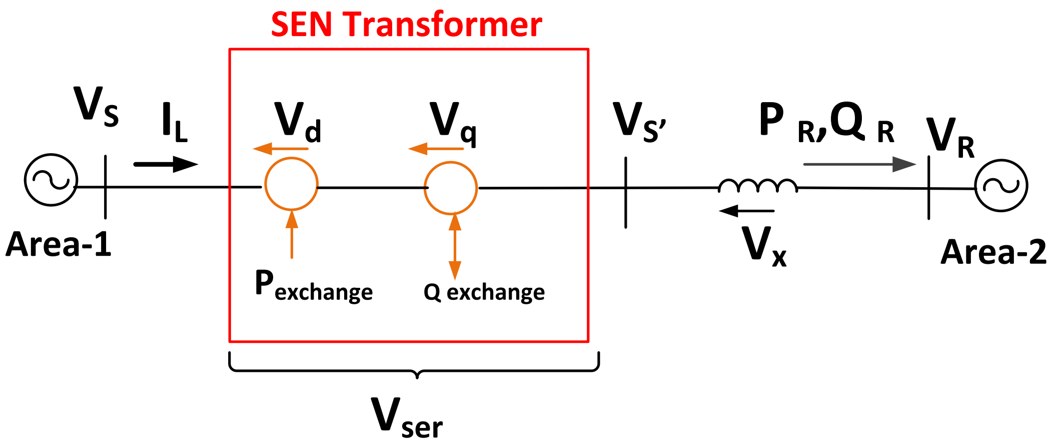


Figure 2.21: Sen Transformer implemented in two area system

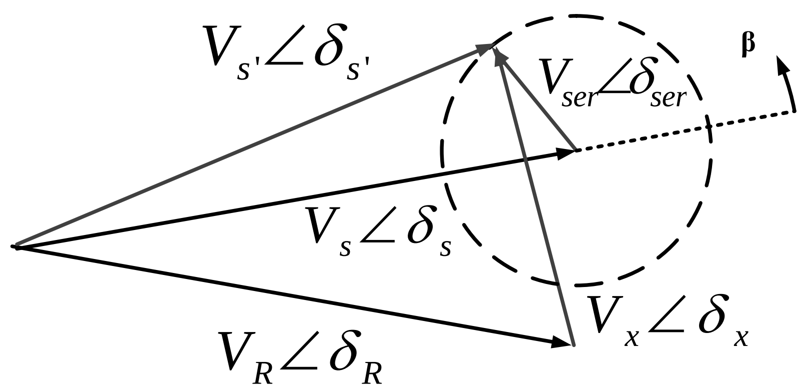


Figure 2.22: Sen Transformer phasor diagram

A detailed construction scheme for voltage injection (v_{ser}) in each phase is explained as follows. The voltage regulating unit with multiple series windings will reflect the current and overall compensation range of the Sen Transformer. In detail the primary phase A series winding voltage (V_{sa}) will magnetically couple to the voltage regulating unit winding of a different phase, which will produce the resultant compensated phase A voltage ($V_{sa'}$).

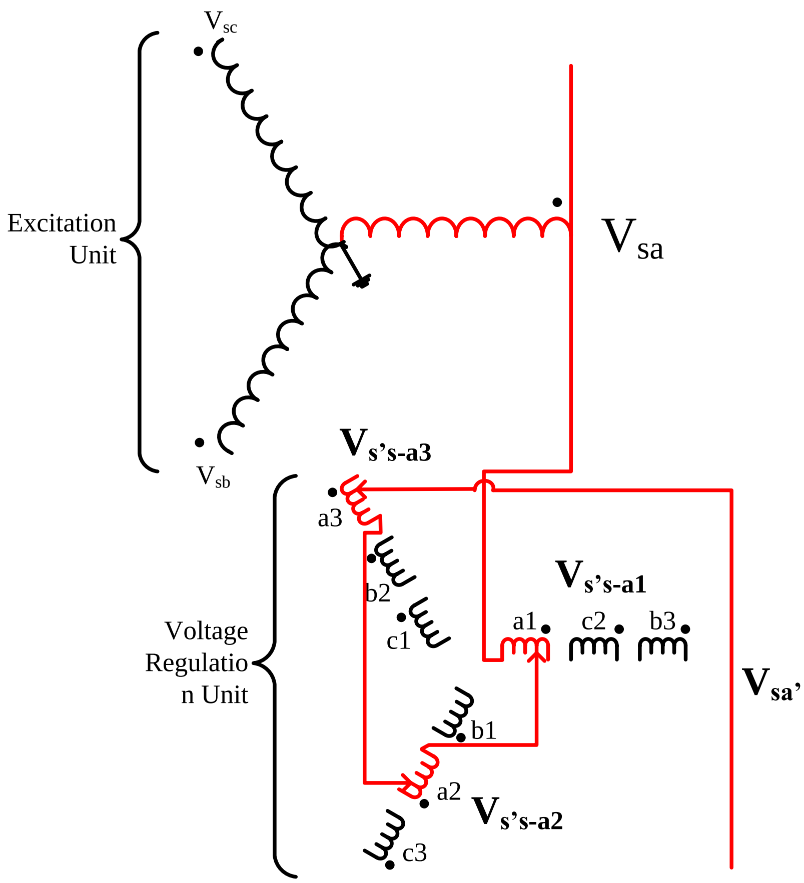


Figure 2.23: Sen Transformer phase A connection

Similarly the other excitation windings' voltages are magnetically coupled to their respective ($< b1, b2, b3 >$ and $< c1, c2, c3 >$) windings to produce the desired voltages. The V_{ser} voltages ($V_{sa'}, V_{sb'}, V_{sc'}$) are 120° apart from each other and their magnitudes are controlled by their respective tap settings. For balanced operation, the tap settings of each winding ($< a1, b1, c1 >$) will have similar configurations and positions. To achieve the compensation

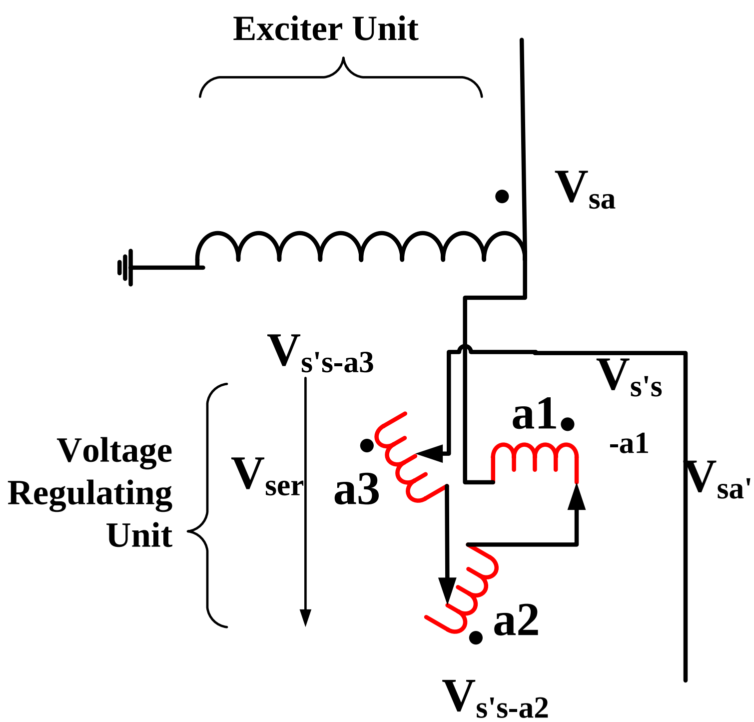


Figure 2.24: Sen Transformer phase A tap position

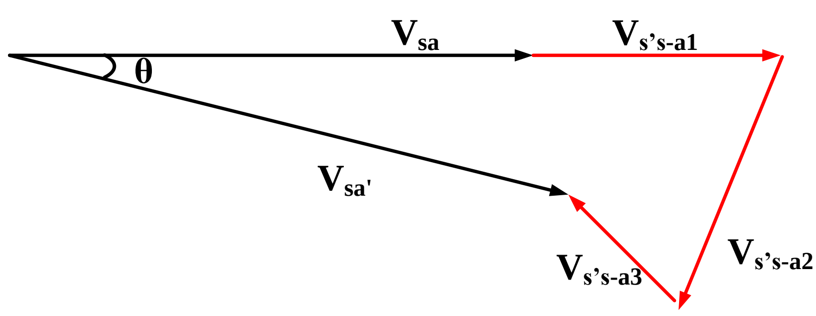


Figure 2.25: Sen Transformer phase A respective phasor diagram

voltage in the same phase ($< a1, a2, a3 >$), the tap settings and positions will be made to differ in at least one winding.

Figures 2.24 and 2.25 show the tap effects and the respective changes in the magnitude of the phase A connection. Along with magnitude, the Sen Transformer is capable of producing a 360 ° phase shift if required. As per the utility's requirement and for the rated power flow, the required voltage phase shift is 0 °to 120 °. This is achieved with two series windings in the voltage regulating unit. The voltage regulation angle (β) is varied between multiple ranges by varying polarities as well as by removing the series winding. The permissible β ranges are 0 ° to 120 °, 120 ° to 240 °, 240 ° to 360 °, −60 ° to 60 °, 60 ° to 180 °, and 180 ° to 300 °. Another advantage with two series windings is that the savings in design will make it cost effective compared to the full design mode.

To understand the operation of the Sen Transformer in two series winding modes, Figures 2.28, 2.27, 2.28 and 2.29 are provided for the unit operation in 120 ° to 240 ° and 240 ° to 360 ° modes with respective phasor diagrams.

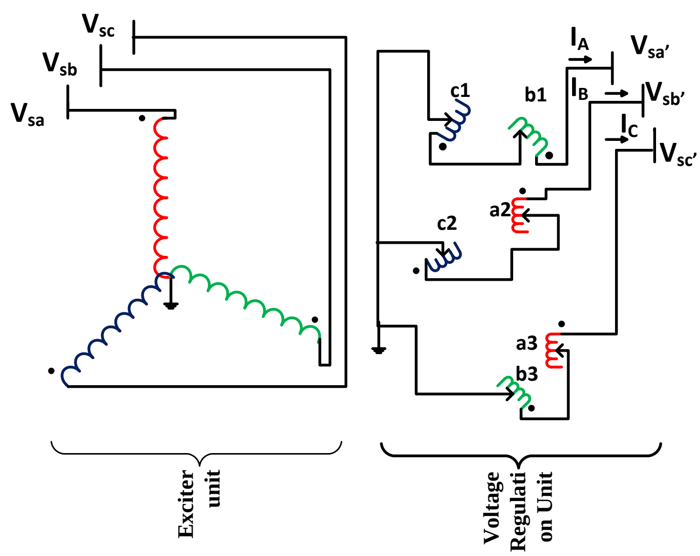


Figure 2.26: Sen Transformer for voltage compensation in entire control range of 120 to 240 degrees

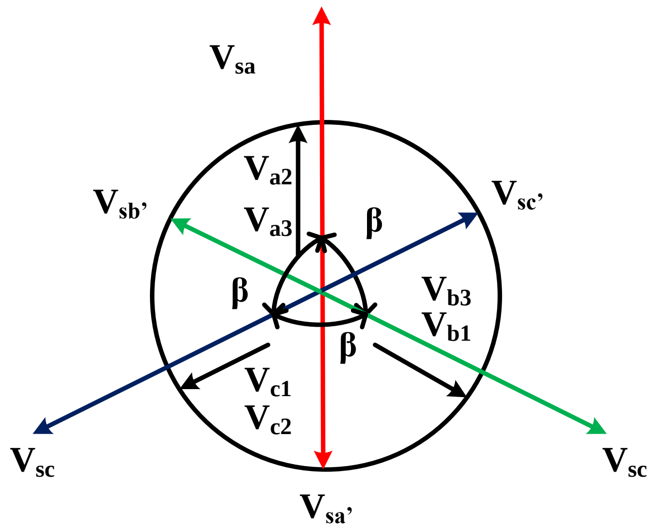


Figure 2.27: Phasor diagram of Sen Transformer operated in control range of 120 to 240 degrees

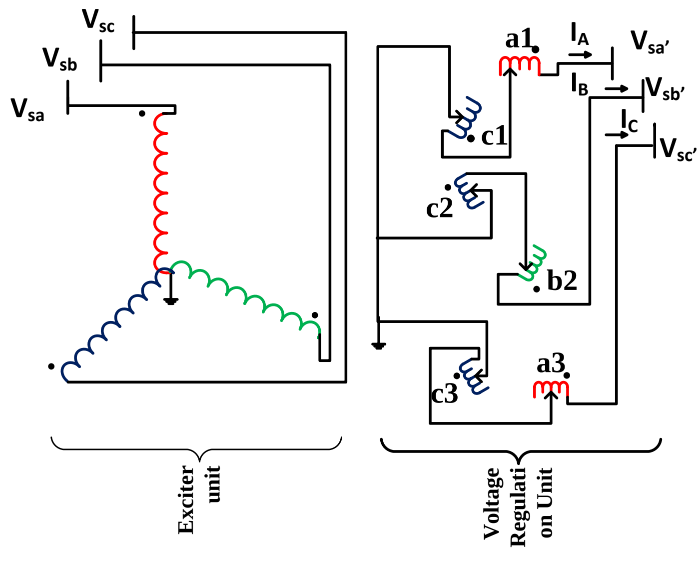


Figure 2.28: Sen Transformer for voltage compensation in entire control range of 240 to 360 degrees

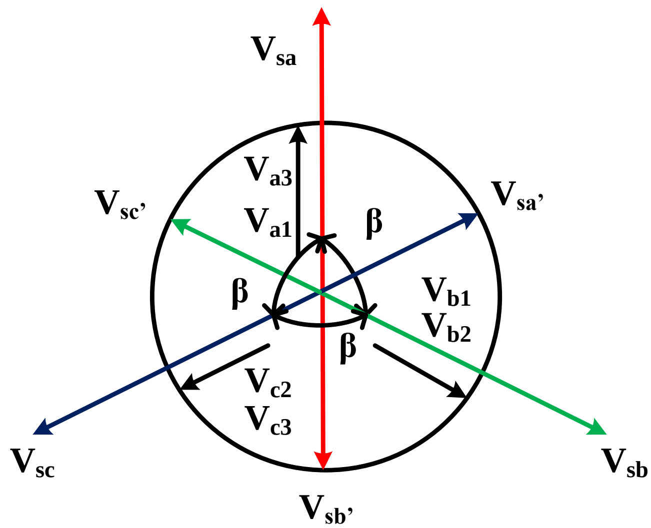


Figure 2.29: Phasor diagram of Sen Transformer operated in control range of 240 to 360 degrees

2.8.2 Design of the Sen Transformer

There is no Sen Transformer model available in either PSS/E or PSCAD/EMTDC. PSCAD allows the user to build custom models from existing blocks in the master library. Individual single phase transformers (9 units) with on-load tap changers on the secondary were each used to design a three-phase Sen Transformer. A 0.0625 pu step was set in the tap changers' design. For the winding connections, the Sen Transformer reference model was used [29]. It was modeled as 9 single phase units in PSCAD/EMTDC. The mutual flux effects, saturation and inrush models are neglected in this study to simplify the model building. The transformer leakage impedance are typically 5-7%, but instead a leakage impedance value of 10% was used to account for some of the simplifications made in the model.

2.9 Summary

In this chapter, number of series compensating devices were discussed as they were developed. Though the traditional, simple compensated devices produce a cheaper compensation cost, they raise stability issues in the system. The emerging technology of thyristors and inverter and converter technology although very effective provide pricey solutions to these issues. Since utilities are always looking for devices of lower capital costs, a recently proposed FACTS device, the Sen Transformer, which is claimed as a very cost effective option was also modeled. The modeling of each FACTS device was explained in detail. In the next chapter, all these device models are placed in a test system and studied to evaluate the benefits of each of these devices for loss minimzation and voltage support as well as discuss their cost effectiveness for use by utilities'.

Chapter 3

System Studies

3.1 Introduction

The previous chapter explained various types of power flow controllers and their principles. In this chapter, loss minimization using the power flow controllers is discussed. Shorter transmission are used for compensation, which would provide the benefit of using smaller rated power flow controllers. This methodology effectively regulates the power flow and also serves maximum amount of load compared to other, longline (traditional) compensation technique. Initial capital investment costs are also reduced because of choosing smaller rating devices, and operation/maintenance costs, etc. are also going to be less.

Economical operation is primarily affected by optimal placement of the device. Multiple techniques are available for determining the optimal placement of FACTS devices in a distribution system. Among them, line stability index-based selection criteria were used for determining the optimal placement. This method identifies an appropriate transmission line among several short lines available in the system for compensation.

A real utility 12 bus system was used for testing. Major FACTS devices were modeled in the commerical (PSS/E) software environment developed by Siemens and similar PSAT developed by Powertech . PSS/E has some good in built library components to develop both steady-state and dynamic models of existing commercial power flow control devices. The FSC, PAR Transformer, and power electrocnic based devices like TCSC, SSSC and UPFC are modeled in both PSS/E and PSAT . However, the Sen Transformer design requires three single core units with multiple secondary windings (or) three phase transformer with three primary windings and nine secondary windings which was found to be difficult to model in PSS/E and PSAT, so this particular device was modeled in electromagnetic transient simulation software (PSCAD/EMTDC) environment, which had components available to model this kind of a special transformer configuration. Also in order to get a proper comparison of the results, both the Sen Transformer and the UPFC model, which have similar power flow control capabilities, were designed in PSCAD/EMTDC and the results were compared. Further their operating range was limited to 240-360 degrees to get a proper comparison of the results.

3.2 12 Bus System

Figure 3.14 shows a single line representation of the proposed realistic 12 bus test system. The test system combines the configuration of three areas (generation and loads), where area 1 represents Manitoba Hydro, area 2 represents North Dakota and Minnesota and area 3 is the Chicago area. This model was developed by Jiang, Annakkage and Gole at the University of Manitoba [39].

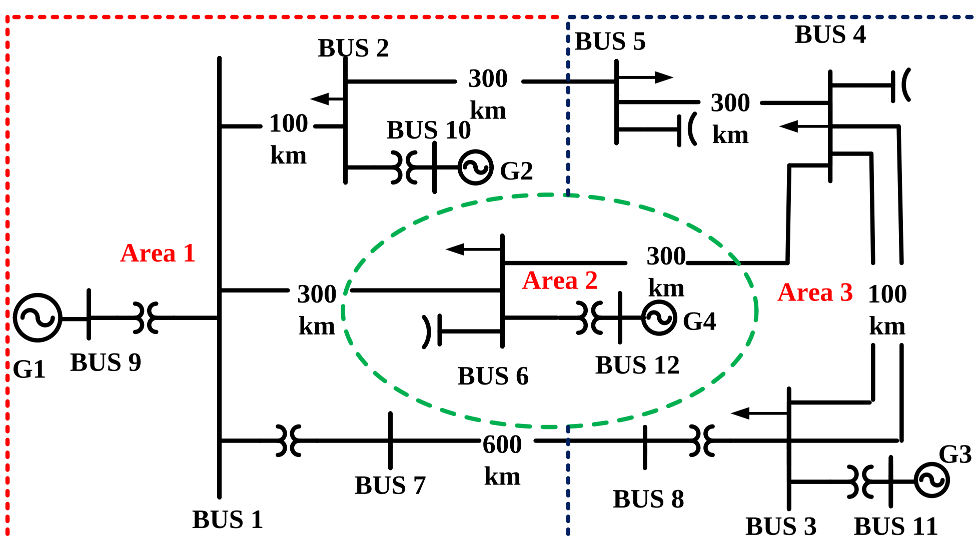


Figure 3.1: 12 bus system

In the proposed test system, area 1 (Manitoba Hydro) has excessive generation while areas 2 and 3 (North Dakota, Minnesota and Chicago) are major load centers. Overall, the test system consists of 4 generators, 6 transformers, 5 load centers, 8 transmission lines and 3 shunt VAr compensators for reactive power support. There are three transmission voltages in the system, i.e. 22 kV (from generating point to nearby step-up transformer), 230 kV (all lines except line 7-8) and 345 kV (line 7-8). The 230 kV line parameters are based on the Manitoba Hydro Glenbro-South to Rugby Winnipeg station line. The 345 kV line design is based on the typical structure of the EPRI transmission line reference book [39]. The transmission line parameters were calculated using equivalent PI (π) representation.

3.2.1 Overall losses

The test system operating conditions are given in Appendix A. Table 3.1 tabulates the real and reactive power flows on the different transmission lines in the system. A modified Gauss-Seidel technique was used to solve the power flow in the test system [40]. For the studies, the transformer tap changers were enabled to adjust the voltage in the system. As well, the other area interchanges and switched shunt adjustments are locked at the setting limitations. The individual line losses are measured and tabulated for reference. Overall, a 49.8 MW line loss was identified in the system. This loss is the most significant portion (99%) of the overall system loss (49.92 MW); with the remaining miscellaneous losses occuring in the devices itself in the system, i.e. the transformer, shunt compensator, etc. The impedances used for the transformers and components are given in Appendix A.

The above result provides a clear view on how the losses are distributed among transmission line loss and the device losses. The individual rating effect of the power flow controller and the respective savings are discussed separately in the following sections.

3.2.2 Bus voltages

According to the Section 3.2.1 line flows, the heavily loaded area 3 was served by area 1 generation. This is reflected in high voltage on the area 1 bus (bus 1, 2, 7 and 9) and low

Table 3.1: Transmission line flows (PSS/E)

From Bus	**To Bus**	$P_S(MW)$	$Q_S(MW)$	$P_R(MW)$	$Q_R(MW)$	**Loss (MW)**
1	2	30.6	36.9	30.9	-53.3	0.3
1	6	210.4	21.7	-195.9	36.7	14.5
2	5	189.1	7.2	-176.7	36.22	12.4
3	4(1)	96.5	18	95.3	25.9	1.2
3	4(2)	96.5	18	95.3	25.9	1.2
4	5	74.7	-15.8	76.7	-19.6	2.0
4	6	55.9	-17.6	-54.8	-26.2	1.1
7	8	330.0	86.4	312.9	72.2	17.1
Total transmission loss (MW)						**49.8**

voltage in area 3 (bus 3, 4 and 5). Figure 3.2 shows the appropriate bus voltages in area 3 (specifically bus 4 and 5), which are affected hugely by high loading with less generation available (200 MW generation and 740 MW load) in the area.

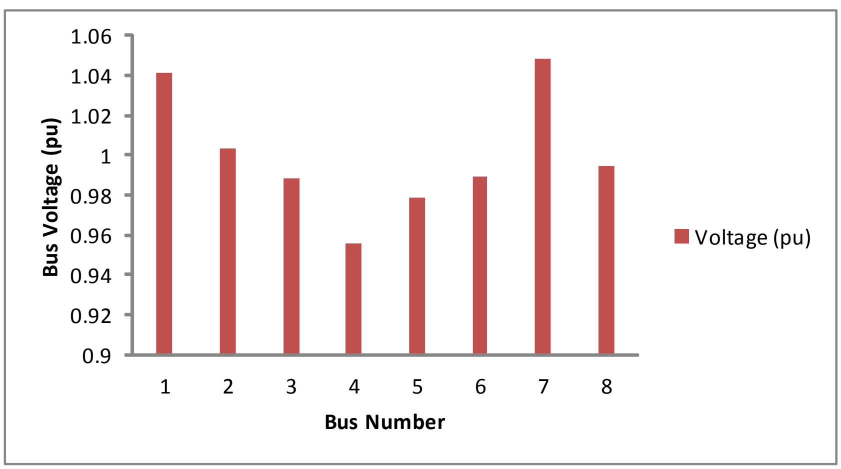


Figure 3.2: Steady state bus voltages

Table 3.1 identifies the weak bus (bus 4 (0.956 pu)) in the system and also shows that bus 4 and 5 voltages are below system average (0.99 pu).

Table 3.2: Transmission line bus voltages

Bus Number	**Reference voltage (kV)**	**Nominal voltage, kV (pu)**	**Phase angle, (δ) (Degrees)**
1	230	239.2 (1.041)	-2.7
2	230	230.79 (1.003)	-0.9
3	230	222.27 (0.988)	-38.3
4	230	219.88 (0.956)	-43.4
5	230	225.11 (.979)	-31.0
6	230	227.54 (.989)	-34.6
7	345	361.65 (1.048)	-4.4
8	345	343.23 (.995)	-36.5

Improving these weak voltages (bus 4 voltage from 0.956 pu to 1.0 pu) will help to transfer more power as well as maintain healthy voltages in the system.

3.2.3 Transmission line loading

Excessive generation in area 1 was used to serve the load in area 3. The available transmission corridors from area 1 to area 3 (from bus 1 to 4) are through buses 1-2-5-4 (corridor 1), 1-6-4 (corridor 2), and 1-7-8-3-4 (corridor 3). Based on the transmission line's surge impedance limits given in Section 1.3, corridor 3 was identified as the most suitable path for delivery to area 3.

Table 3.3 gives the line loading percentages for the different branches in the test system. The line loading percentage is calculated based on the maximum MVA rating (based on St.Clair curve) given in Appendix Table A.5 [41]. By comparing these results in Table 3.3 and assessing customer loads, it has been identified that the power flow was unevenly distributed and causing overloading in some transmission lines (with load growth). A 75% load limit criteria was used for the transmission lines in the system to take into account the other components which have a further lower rating [transformer ratings(winter and summer), switches, auto-reclosures] on the line. Since line 7-8 is a higher-rated transmission line in the system, it has more room for the power flow. But due to uneven distribution of power flow, the line was underutilized in corridor 3. Figure 3.3 identifies how the other lines 1-6 and 2-5 are overloaded and as a result the losses are more and also the possibility of system security violation.

Table 3.3: Transmission line loss

Branch	**Line loading**
1-2	25%
1-6	81%
2-5	75%
3-4(1)	41%
3-4(2)	41%
4-5	32%
4-6	25%
7-8	65%

Similarly, future load growth in these areas will increase even the existing losses and complicate the power flow. To avoid these scenarios, a redistribution is recommended and will be achieved through power flow controllers. The following line selection criteria will identify the optimal placement of the devices and explain their capability to manage loss minimization and stability.

3.3 Line Selection Criteria

In general, as discussed in Section 1.5, the majority of compensation locations are based on the longer and higher-rated transmission lines available in the system. This is possible if the utility has large monies available its disposal for capital investment, which is not the case usually. These lines carry maximum power and have high stability ratings compared

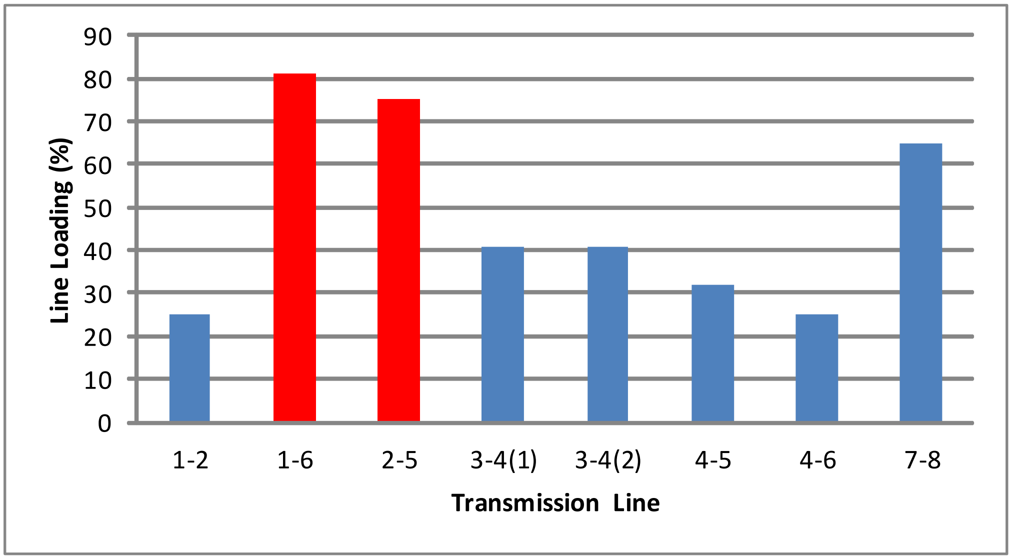


Figure 3.3: Transmission line loading

to other transmission lines in the system. Compensating these transmission lines costs more due to device construction, operation and maintenance. Failure of these devices will cause severe contingencies (which vary with the transfer power limits) and may lead to the failure to serve uninterrupted loads (if any). The probability of this occurrence will be lower with compensation for short transmission line. To avoid these issues, a new proposed approach of compensating the smaller transmission line is explained in this thesis. This approach will serve the same requirements as well as add benefits economically.

In the case of multiple short transmission lines in a system, a set of line selection criteria was used for optimal line selection. The formulae and other advantages of this method were explained in Section 1.5.1. For the proposed 12 bus test system, line stability index values are calculated for all lines and refined to a best-fit smaller transmission line (in green) in Table 3.4.

In the selection criteria definition, a line index close to 1 will have lower stability, and vice versa. Since lines 3-4 have lower values and close to zero, they are more suitable for the placement of devices. Now, the historical approach (line 7-8 compensation) and the

Table 3.4: Transmission line selection

Transmission Line	**Length**	**Line stability Index** (L_{MN})
1-2	100	0.18815
1-6	300	0.48442
2-5	300	0.48374
3-4 (1)	100	0.06866
3-4 (2)	100	0.06866
4-5	300	0.18290
4-6	300	0.29336
7-8	500	0.59680

proposed approach (line 3-4 compensation) will be tested and the results will be compared to validate the proposed optimal location selection approach.

3.4 Non-thyristor Based Power Flow Controllers

First, simple non-thyristor based FACTS devices (the Fixed Series Capacitor [FSC] and the phase angle regulating [PAR] transformer) are tested for preliminary comparison. The device ratings and level of compensation were calculated from the formulae stated in Sections 2.2 and 2.3. Again, these test systems and the power flow controllers are designed in PSAT (DSA tools) and compared with the PSS/E environment.

3.4.1 Fixed Series Capacitor

A Fixed Series Capacitor was placed in two individual lines to validate the proposed approach. At first, a 108.44 Ω (k = 0.2, refer Equation 2.6) rated FSC bank was placed on line 7-8 for corridor 3 compensation (traditional). Table 3.5 identifies the resultant line flow improved with a 245 MVAr rated reactive power compensation capacitor. Similarly, 2 * 48.197 Ω (k = 0.8, refer Equation 2.6) were placed in line 3-4 for compensation (proposed).

This compensation provided a 114 MVAr support (2 * 57 MVAR) to the test system.

Table 3.5: Overall loss with FSC compensation

Compensation	**Level of Compensation**	**Generation (MW)**	**Load (MW)**	**Loss (MW)**	**Savings (kW)**
No Compensation	0	1509.8	1460	49.8	-
Line 7-8	20	1509.35	1460	48.56	1690
Line 3-4	80	1508.64	1460	48.64	2320

Table 3.5 also explains the resultant loss reduction by the proposed short line compensation. Comparing losses, the required generation of 1509.35 MW for line 7-8 compensation is slightly lower than no compensation generation and the overall saving is close to 1690 kW, whereas for line 3-4 compensation there is a significant reduction in generation achieved (1508.4 MW) with overall savings of 2320 kW. Overall, the proposed approach achieves maximum loss reduction (including the required generation reduction) with fixed series compensation. Even with 80 % compensation of line 3-4, the overall device rating is far lower compared to other long line compensation.

3.4.1.1 Bus voltages with FSC compensation

Table 3.6 shows bus voltages with fixed series compensation. With reference to the loss reduction improvement in line 3-4 compensation, there is a subsequent power flow increase noticed on corridor 3. As a result, all area 3 bus voltages are improved correspondingly. Figure 3.4 shows the improvement in area 3 bus voltage with FSC compensation in line 3-4.

Table 3.6: Bus voltages with FSC compensation

Bus	No compensation voltage (pu)	Line 7-8 Compensation voltage (pu)	Voltage with line 3-4 Compensation (pu)
1	1.041	1.038	1.040
2	1.008	1.004	1.004
3	.988	.991	.989
4	.956	.963	.981
5	.979	.996	1.008
6	.989	.991	.992
7	1.048	1.044	1.047
8	.995	1.0013	.995

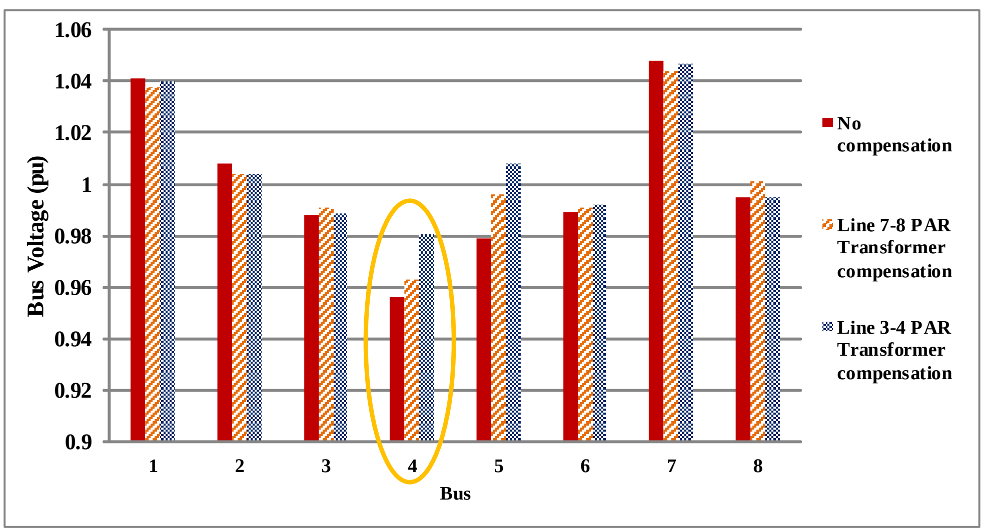


Figure 3.4: Bus voltages with FSC compensation

Bus 4 (identified as the weakest bus in the system due to its low voltage) was improved from 0.956 pu to 0.963 pu with line 7-8 compensation. On the other hand, with the proposed compensation, the bus voltage improved significantly to 0.981 pu. Therefore, FSC compensation in line 3-4 provided a better voltage profile for the system.

3.4.1.2 Transmission line loading with FSC compensation

Another advantage with FSC compensation is reconfigured power flow. As there was power flow improvement on corridor 3 with FSC compensation, it avoided loop flows. Table 3.7 identifies normal and compensated line loadings. It indicates uneven distribution and line overloading on line 1-6 (81%) and 2-5 (75%).

Table 3.7: Loading on transmission line with FSC compensation

Branch	**Line loading**		
	No Compensation	**Line 7-8 Compensation**	**Line 3-4 Compensation**
1-2	25%	23%	23%
1-6	81%	78%	78%
2-5	75%	71%	73%
3-4 (1)	41%	42%	41%
3-4 (2)	41%	42%	41%
4-5	32%	29%	30%
4-6	25%	21%	21%
7-8	65%	69%	68%

Figure 3.5 compares the flow with traditional and proposed compensation.

The results conclude that with line 7-8 compensation, the loading on 1-6 and 2-5 was reduced 3% and 4% respectively, whereas with line 3-4 compensation, a similar 3% and 2% load relief was achieved with a lower-rated device. Along with these two heavily loaded lines, line 3-4 provided similar load relief compared to the other line by re-regulating the power flow.

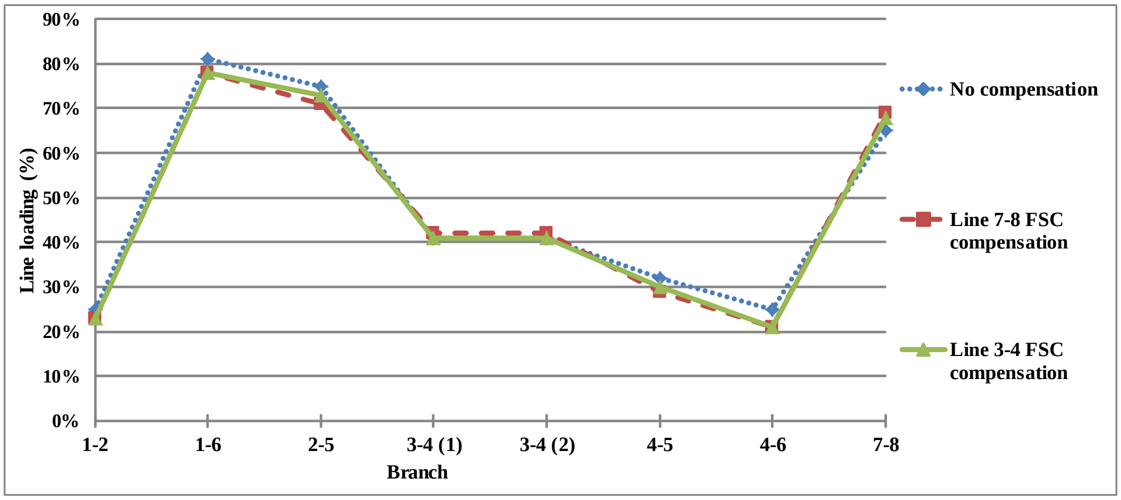


Figure 3.5: Transmission line loading with FSC compensation

3.4.2 Phase Angle Regulating (PAR) Transformer

After examining FSC compensation, two differently-rated PAR transformers were used to test losses on the conventional and proposed locations. The conventional approach used a 120 MVA phase angle regulating transformer to compensate line 7-8 and the second approach used 2* 30 MVA PAR transformers to compensate line 3-4. The resultant quadrature voltages injected through the exciter unit for both approaches were calculated based on the formulae in Section 2.3. The injected voltages achieved a -14° (for line 7-8) and -9° (for line 3-4) phase shift by their respective PAR's for compensation.

Table 3.8: Overall loss with PAR compensation

Compensation	**Phase shift (degrees)**	**Generation (MW)**	**Load (MW)**	**Loss (MW)**	**Savings (kW)**
No Compensation	0	1509.8	1460	49.8	-
Line 7-8	-14	1508.56	1460	48.56	2360
Line 3-4	-9	1507.4	1460	48.5	2450

Table 3.8 gives the resultant loss reduction with line 7-8 compensation, including generation savings, as 2360 kW. On the other hand, with line 3-4 compensation the resultant loss reduction (including generation savings) is 2450 kW. Even though the second approach of compensating line 3-4 uses just a $\frac{2}{3}^{rd}$ rating transformer compared to the first approach, the resulting loss minimization is far better compared to the first.

3.4.2.1 Bus voltages with PAR compensation

Table 3.9 explains the resultant voltage levels with quadrature voltage injected in the compensated line. Overall, the bus voltages are significantly regulated with a PAR transformer. This allows maximum active power flow (compared to the uncompensated mode) by minimizing the reactive power flow in the line.

Table 3.9: Bus voltages with PAR compensation

Bus	**No compensation voltage (pu)**	**Line 7-8 Compensation voltage (pu)**	**Line 3-4 Compensation voltage (pu)**
1	1.041	1.0388	1.0392
2	1.008	1.0051	1.005
3	.988	.9863	.9863
4	.956	.9608	.96
5	.979	1.0104	1.008
6	.989	.9927	.9924
7	1.048	1.0438	1.0447
8	.995	.9898	.99

Again, the weak bus (bus 4) voltage levels are compared in Figure 3.6, which identifies an improvement. In detail, with line 7-8 compensation, the voltage improved from 0.956

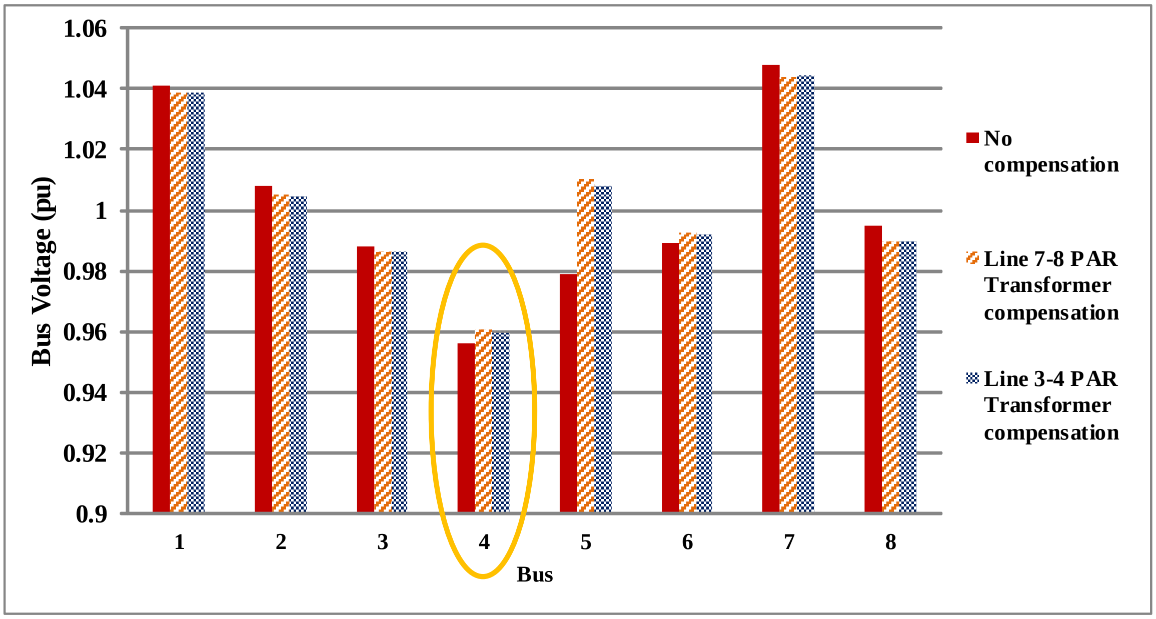


Figure 3.6: Bus voltage with PAR compensation

pu to 0.961, whereas with the other, the same voltage reached 0.96 pu with the low rating transformer.

3.4.2.2 Transmission line loading with PAR compensation

Table 3.10 represents redistribution and relief for overloaded lines in the test system. Though the series transformer adds series impedance to the compensated line, the series injected voltage (phase shifted) compensates the reactive power flow and boosts the active power.

The line loading plot in Figure 3.7 clearly presents the improvement in transmission line flows with compensation as well as the load relief on heavily loaded lines. Line 3-4 compensation relieved the heavily loaded lines 10% (line 1-6) and 7% (line 2-5), whereas in the other case, it was 7% on both lines.

Since the transmitted active and reactive power flow depends on the sending and receiving end voltages, the placement of the PAR will regulate the power flow in a more stable manner

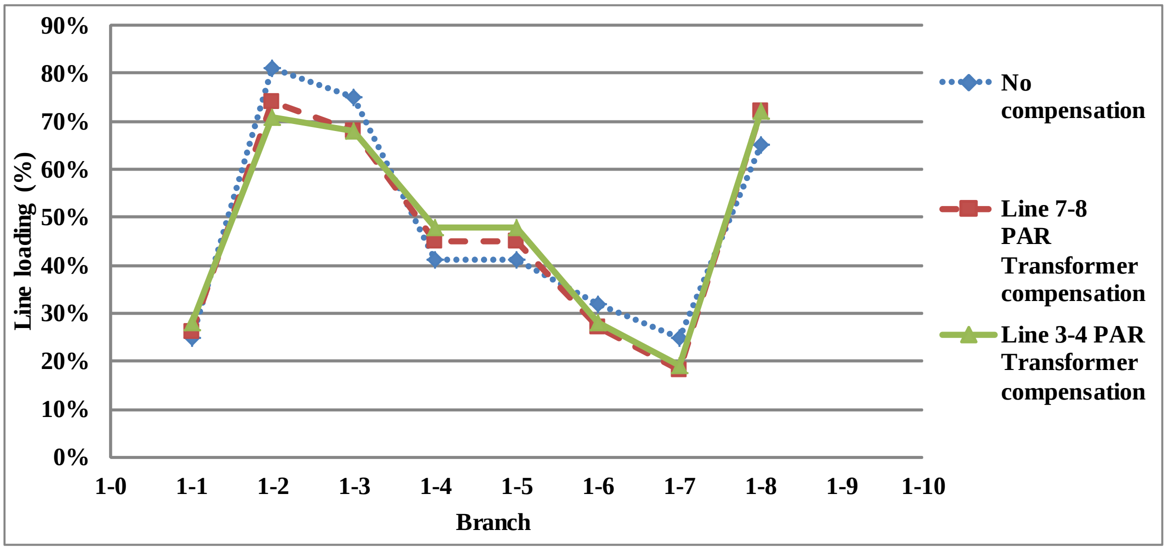


Figure 3.7: Transmission line loading with PAR compensation

(with load tap changers). Comparing the results, line 3-4 achieves optimum power flow on all lines along with maximum power transfer capacity.

Table 3.10: Loading on transmission line with PAR compensation

Branch	**Line loading**		
	No Compensation	**Line 7-8 Compensation**	**Line 3-4 Compensation**
1-2	25%	26%	28%
1-6	81%	74%	71%
2-5	75%	68%	68%
3-4 (1)	41%	45%	48%
3-4 (2)	41%	45%	48%
4-5	32%	27%	28%
4-6	25%	18%	19%
7-8	65%	72%	72%

3.5 Thyristor Based Power Flow Controllers

As discussed in Chapter 2, thyristor-based compensating devices built with special features compare to non-thyristor based devices and boost economical operation with more system security. Devices like the Thyristor Controlled Series Capacitor (TCSC), Thyristor Controlled Series Reactor (TCSR), Thyristor Switched Series Capacitor (TSSC), Thyristor Switched Series Reactor (TSSR), and Gate Turn off Controlled Series Capacitor (GCSC) all fall in this category. Among them all, the TCSC provides maximum series compensation and sharp response, and mitigates the stability problems as previously discussed. With all these benefits, the TCSC is the most widely used series compensator after the FSC.

3.5.1 Thyristor Controlled Series Compensator (TCSC)

The design specification of the TCSC depends on the line MVA and the firing angles fed to the thyristor banks. 100 MVAr TCSC blocks were installed to quantify the losses in line 7-8. In the design of the TCSC, the typical capacitor bank reactance (X_{net}) lies at 30 Ω per phase and is based on rated continuous current (I_L), i.e. 1500 A (approximately). The capacitor bank and parallel inductance are calculated based on the list of formulae stated in Section 2.4.

Similarly, 60 MVAr (2 * 30 MVAr units) were placed on the shorter transmission line (line 3-4). Both these devices are operated in capacitive mode with thyristors operating on an inductive path. This injects reactive power into the system and regulates the active power flow along the line. Table 3.11 explains the resultant loss minimization savings: with compensation, 1690 kW (1509.35 MW generation) for line 7-8 and 2320 kW for line 3-4 (1508.64 MW generation).

Table 3.11: Overall loss with TCSC compensation

Compensated line info	**Generation (MW)**	**Load (MW)**	**Loss (MW)**	**Savings (kW)**
No Compensation	1509.8	1460	49.8	-
Line 7-8	1509.35	1460	48.56	1690
Line 3-4	1508.64	1460	48.64	2320

The results observed from the TCSC loss reduction comparison are similar to the FSC comparison, and line 3-4 provided a better loss reduction of 2320 kW (compared to 1690 kW). Though the result matches, the design ratings and characteristics stand apart from the simple capacitor compensation.

3.5.1.1 Bus voltages with TCSC compensation

Injected reactive power is constantly monitored by the TCSC firing angle control to control the net reactance of the line. This allows maximum power transfer to area 3 and improves the voltage profile in this area. Table 3.12 identifies the voltage improvement with different TCSC operations.

Figure 3.8 identifies that the TCSC compensation improved the low voltage bus (bus 4) from 0.956 pu to 0.963 pu with line 7-8 compensation. Similar compensation achieved a 0.981 pu improvement with a lower-rated device. The result strongly suggests that the weak bus (bus 4) voltage improved significantly in the proposed approach compared to the traditional approach.

Table 3.12: Bus voltages with TCSC compensation

Bus	No compensation voltage (pu)	Line 7-8 Compensation voltage (pu)	Voltage with line 3-4 Compensation (pu)
1	1.041	1.038	1.040
2	1.008	1.004	1.004
3	.988	.991	.989
4	.956	.963	.981
5	.979	.996	1.008
6	.989	.991	.992
7	1.048	1.044	1.047
8	.995	1.0013	.995

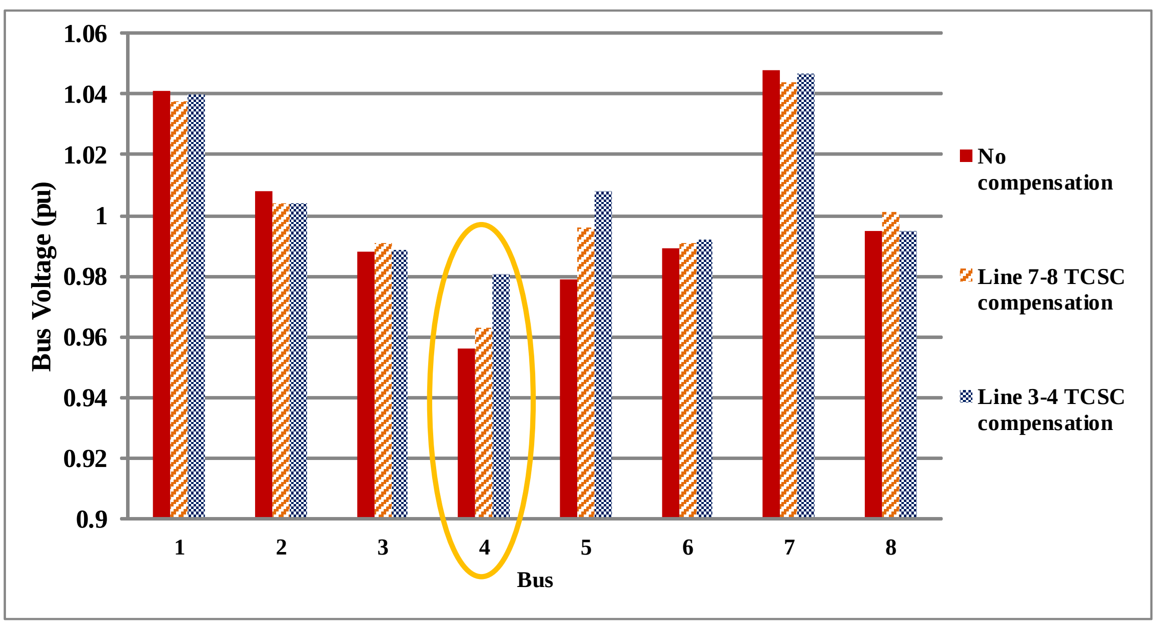


Figure 3.8: Bus voltages with TCSC compensation

3.5.1.2 Transmission line loading with TCSC compensation

With improved voltage regulation, the TCSC also provided a more flexible solution for controlling line flows compared to the FSC. This TCR control provided smooth regulation in compensation (inductive or capacitive) in the line and allowed maximum power flow (during capacitive mode only). Table 3.13 shows the improvements in power flow along the test system with the TCSC.

Heavily loaded lines were relieved 3% (line 1-6) and 4% (line 2-5) with line 7-8 compensation. On the other hand, a slightly lower load relief was identified with the TCSC (3% and 2% respectively). Figure 3.5 visualizes the power flow increase in other underutilized transmission lines (more economical distribution) in the test system.

Table 3.13: Loading on transmission line with TCSC compensation

Branch	**Line loading**		
	No Compensation	**Line 7-8 Compensation**	**Line 3-4 Compensation**
1-2	25%	23%	23%
1-6	81%	78%	78%
2-5	75%	71%	73%
3-4 (1)	41%	42%	41%
3-4 (2)	41%	42%	41%
4-5	32%	29%	30%
4-6	25%	21%	21%
7-8	65%	69%	68%

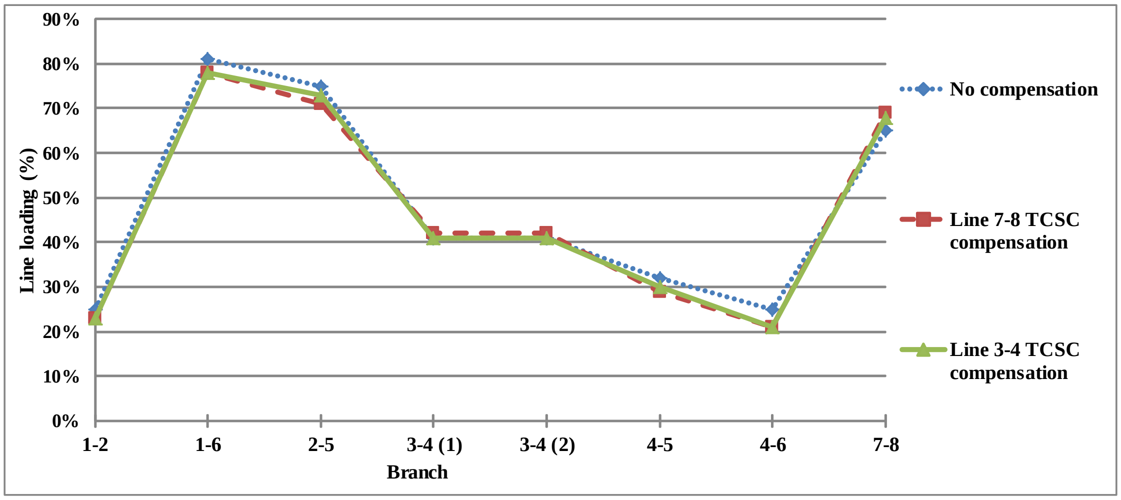


Figure 3.9: Transmission line loading with TCSC compensation

3.6 Voltage Source Converter (VSC) Based Power Flow Controllers

The Voltage Source Converter's (VSC) replaced the thyristor valves with their advance features. These device featured components are capable of managing power system congestion through independent control, multitasking features (voltage support, etc.) and oscillation damping. A Static Synchronous Series Compensator (SSSC) with an external source and a unified power flow controller (UPFC) come under this heading.

3.6.1 Static Synchronous Series Compensator (SSSC)

A series voltage injection based Static Synchronous Series Compensator was used for compensation in the proposed test system. To compensate line 7-8, a 150 MVA SSSC with 0.4 pu voltage injection capacity was used. The injected voltage was 90° out of phase with the line voltage.

Section 2.6 explained the effect of injected voltage on the line compensation process and the rate of increase in the power flow. Also, a DC capacitor (source) was used to regulate the injected power instead of an external source (to minimize the cost as well).

Next, the proposed line 3-4 was compensated with an 80 MVA (2 units of 40 MVA each) SSSC. In this case, the injected voltage was 0.25 pu. Table 3.14 illustrates the improvement in loss minimization: a 5300 kW savings with line 7-8 compensation (1507.5 MW generation requirement) and 4000 kW savings with line 3-4 compensation (1507.8 generation requirement). In both cases, a 1460 MW load was served in all 3 areas presented. Due to large capacity, a slightly improved loss reduction was observed on line 7-8. The device requirement is doubled compared to the proposed approach.

Table 3.14: Overall loss with SSSC compensation

Compensated line info	**Voltage injected (pu)**	**Generation (MW)**	**Load (MW)**	**Loss (MW)**	**Savings (kW)**
No Compensation	0	1509.8	1460	49.8	-
Line 7-8	.4	1507.5	1460	46.8	5300
Line 3-4	.25	1507.8	1460	47.8	4000

3.6.1.1 Bus voltage with SSSC compensation

Table 3.15 indicates the after-effect of the fully controllable series injected compensating voltage on the proposed test system. The injected voltage is independent of the magnitude of the transmission line current. The result shows the voltage boost in compensated lines. In the case of line 7-8, bus 4 voltage rose to 0.97 from 0.956. Also, the other line achieved a 1.016 pu improvement, which is far higher than that of the line 7-8 compensation.

Table 3.15: Bus voltages with SSSC compensation

Bus	No compensation voltage (pu)	Line 7-8 Compensation voltage (pu)	Line 3-4 Compensation voltage (pu)
1	1.041	1.048	1.039
2	1.008	1.008	.993
3	.988	.991	1.007
4	.956	.97	1.016
5	.979	1.038	1.03
6	.989	.996	.998
7	1.048	1.062	1.044
8	.995	.999	.996

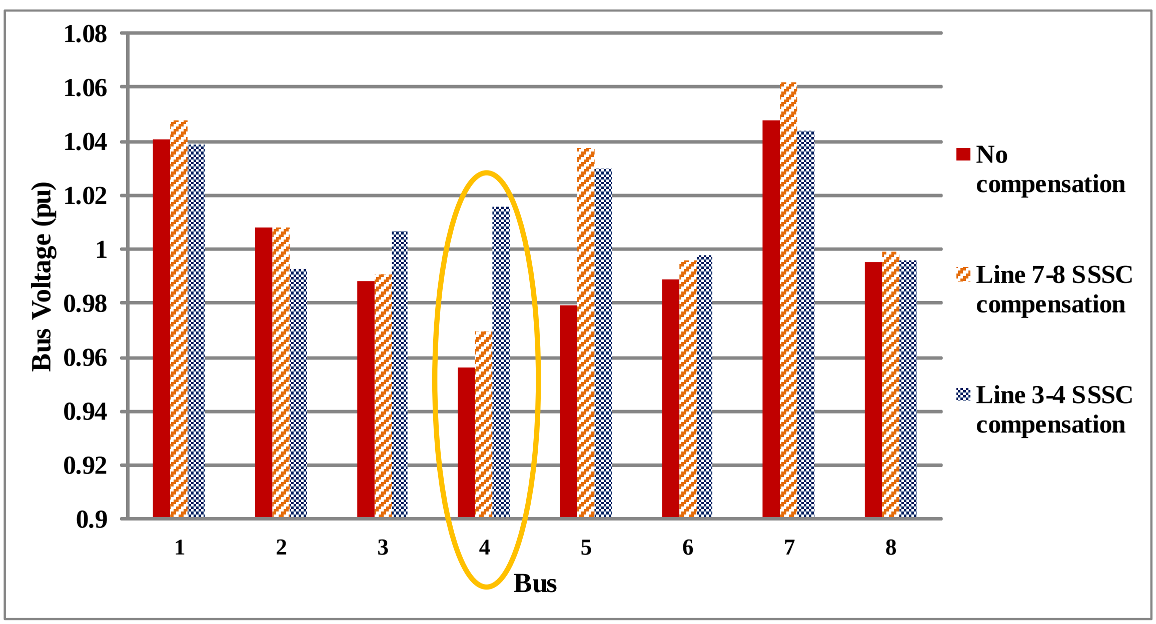


Figure 3.10: Bus voltages with SSSC compensation

Figure 3.10 shows the variation in voltage with the smaller device in other buses in the system. Overall, a better voltage profile is identified for the system with line 3-4 compensation.

3.6.1.2 Transmission line loading with SSSC compensation

Since the SSSC device operates in voltage injection mode, voltage levels are boosted across the test system. The resultant power flow improvement is also observed all along the branches. Table 3.16 explains the SSSC power flow control (increased power flow) for the compensated lines.

Table 3.16: Loading on transmission line with SSSC compensation

Branch	**Line loading**		
	No Compensation	**Line 7-8 Compensation**	**Line 3-4 Compensation**
1-2	25%	35%	28%
1-6	81%	63%	68%
2-5	75%	63%	68%
3-4 (1)	41%	53%	46%
3-4 (2)	41%	53%	46%
4-5	32%	26%	27%
4-6	25%	15%	18%
7-8	65%	78%	74%

Figure 3.11 identifies overall power distribution across the test system. The heavily loaded lines are relieved (line 1-6, 81% to 63%, and line 2-5, 75% to 63%) and power is optimally distributed all along the system.

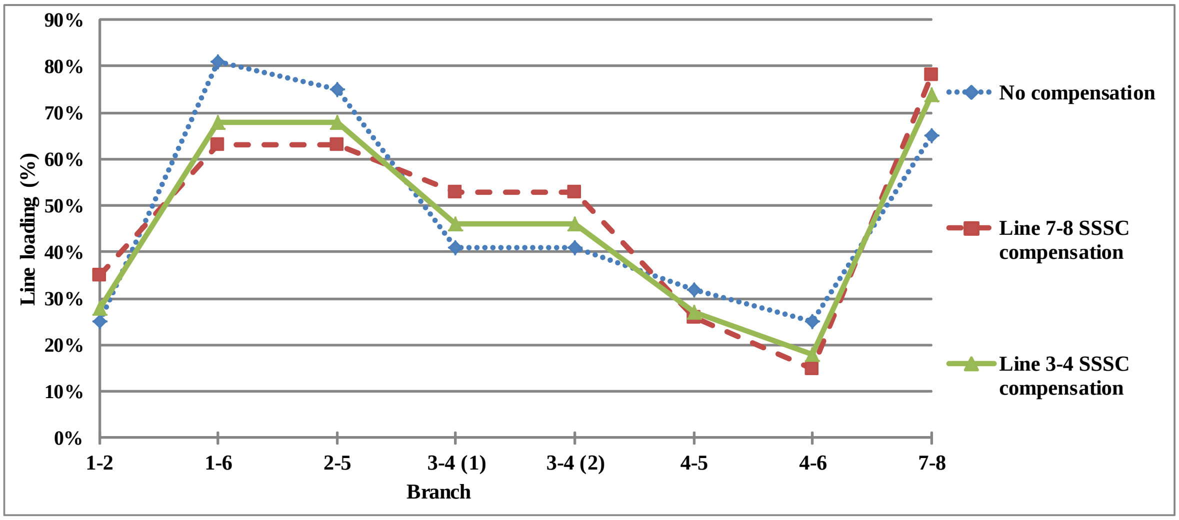


Figure 3.11: Transmission line loading with SSSC compensation

Line 3-4 compensation achieved similar load flow regulation (line 1-6, 81% to 68%, and line 2-5, 75% to 68%) to line 7-8 compensation and avoided the loop flows.

3.6.2 Unified Power Flow Controller

Since the SSSC device has certain limitations on injected active and reactive power flow, a UPFC (both shunt and series control device) was implemented for loss minimization. Table 3.17 explains the different UPFC device ratings along with the power flow set points in the system.

A 150 MVA UPFC device was used for line 7-8 compensation with the desired power limits of 375 MW active and 50 MVAr reactive powers. Similarly, two 35 MVA UPFC devices with 100 MW and 20 MVAr limits were used to compensate line 3-4. The desired power flow through the compensated line was set based on compensation requirements and SIL, stability and thermal limits as explained in Section 1.4.

Table 3.17: Overall loss with UPFC compensation

Line Selected	**UPFC Rating**	**Generation (MW)**	**Load (MW)**	**Loss (MW)**	**Savings (kW)**
No Compensation	No device	1509.8	1460	49.8	-
Line 7-8	Shunt Capacity =150MVA, P(Desired)=375MW, Q(Desired)=50MVAr	1507.2	1460	47.2	5200
Line 3-4	Shunt Capacity =35MVA, P(Desired)=110MW, Q(Desired)=20MVAr	1507	1460	47	5400

Based on generation, load and active and reactive power support by the shunt capacitor and UPFC, the resultant savings observed for line 7-8 compensation are 5200 kW, and 5400 kW for line 3-4 compensation. The additional advantage with line 3-4 compensation is the required compensation device rating (47% of line 7-8 UPFC).

3.6.2.1 Bus voltage with UPFC compensation

The shunt connected VSC, i.e. the STATCOM, in the UPFC model significantly regulates the connected bus voltage to pump more power through the compensated line. Figure 3.12 elaborates this voltage regulation effect throughout the system. Table 3.18 shows the UPFC effect on shunt connected bus 7 and 4 (regulated to 1.048 to 1.069pu and 0.995 to 1.003 respectively). The weak bus voltage, bus 4, improved from 0.956 pu to 0.967 (1.2% improvement) in line 7-8 compensation, whereas in the other, line 3-4 compensation, the voltage regulated to 1.079 pu (13% improvement). The results indicate that line 3-4 compensation provides significant regulation and a better voltage profile across the test system.

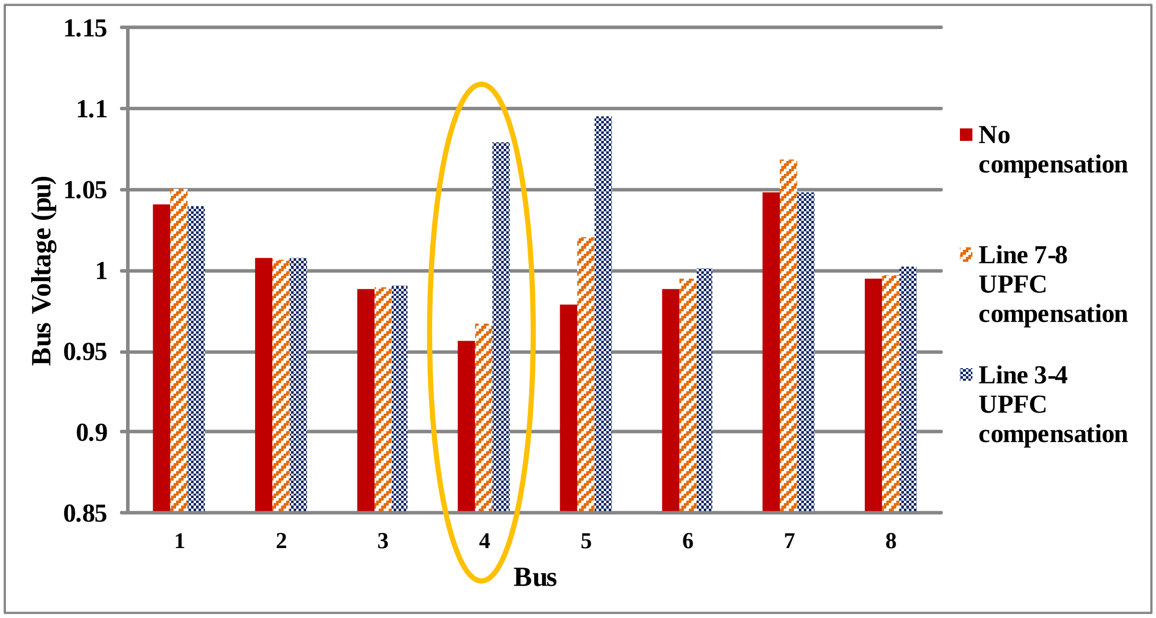


Figure 3.12: Bus voltages with UPFC compensation

Table 3.18: Bus voltages with UPFC compensation

Bus	No compensation voltage (pu)	Line 7-8 Compensation voltage (pu)	Line 3-4 Compensation voltage (pu)
1	1.041	1.051	1.04
2	1.008	1.007	1.008
3	.988	.99	.991
4	.956	.967	1.079
5	.979	1.021	1.095
6	.989	.995	1.002
7	1.048	1.069	1.048
8	.995	.997	1.003

3.6.2.2 Transmission line loading with UPFC compensation

The series component in a UPFC (the SSSC) injects the quadrature voltage to control reactive power in the compensated line. This regulates the power flow of the compensated line, as discussed in earlier sections. Figure 3.13 demonstrates the relief on heavily loaded lines on corridors 1 and 2 (lines 2-5 and 1-6).

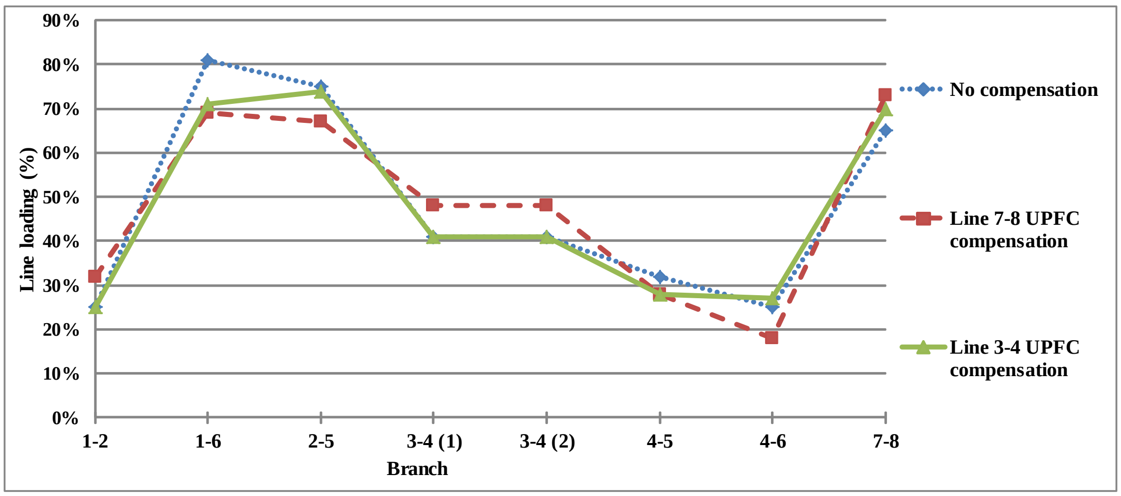


Figure 3.13: Loading on transmission line with UPFC compensation

Table 3.19 shows the improvement in load relief on line 1-6 is 15% (with line 7-8 compensation) and 12.5% (with line 3-4 compensation). Similarly, line 2-5 is relieved by 10.6% and 0.3% respectively. Overall, line 3-4 equally distributed the power and achieved maximum loss reduction.

Table 3.19: Loading on transmission line with UPFC compensation

Branch	**Line loading**		
	No Compensation	**Line 7-8 Compensation**	**Line 3-4 Compensation**
1-2	25%	32%	25%
1-6	81%	69%	71%
2-5	75%	67%	74%
3-4 (1)	41%	48%	41%
3-4 (2)	41%	48%	41%
4-5	32%	28%	28%
4-6	25%	18%	27%
7-8	65%	73%	70%

3.7 12 Bus Model in PSCAD/EMTDC

PSCAD/EMTDC is an electromagnetic transient simulation tool and simulates the network in a transient environment, in comparison to steady state simulating tools like PSS/E and PSAT. Another advantage of PSCAD/EMTDC is its capacity to model both DC and AC components (e.g. FACTS, HVDC and other user-defined configurations) and to capture results in a time domain frame. In general, PSCAD/EMTDC will run the complex algorithms and techniques, and simulate it very quickly (depending on the step size and the details of the components in the simulating program). The advanced GTO and IGBT components (used in converter and inverter design) are readily available as user building components. These components were used to design and test the wide-range operating conditions of advanced FACTS devices like the UPFC and the Sen transformer.

To compare economy of operation and system stability, the 12 bus system was modeled in PSCAD/EMTDC. As shown in Figure 3.14, for required generation, one hydro (G3) and two thermal generators (G2 and G4) were built along with slack bus generation (G1) (three phase voltage sources).

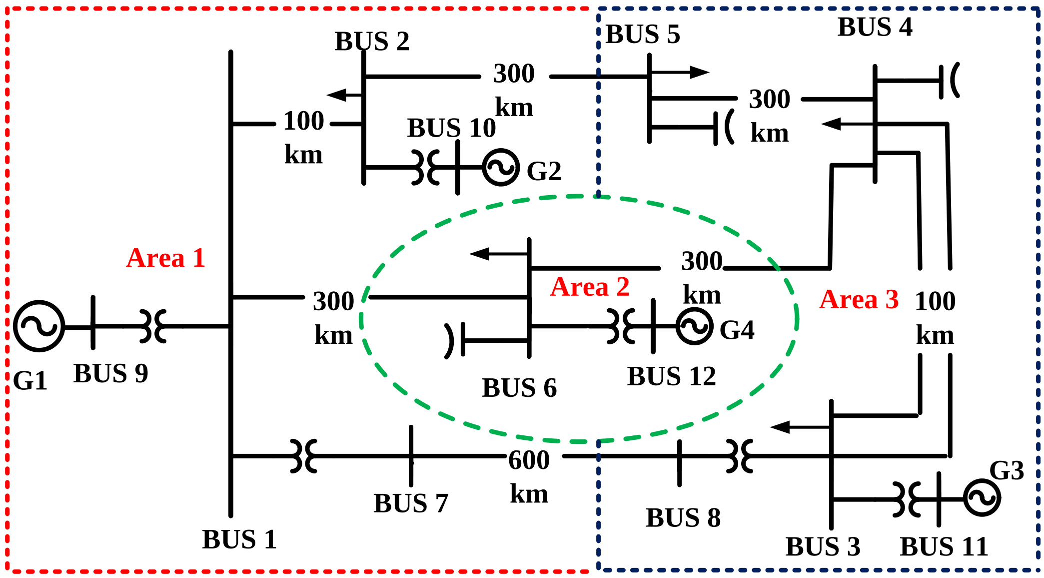


Figure 3.14: 12 bus model in PSCAD/EMTDC

The 230 kV lines were designed with a cardinal conductor aligned on the 3NNHS structure and the 345 kV line with a Drake conductor aligned on the 3NNHS structure for transmission. Along with this, fixed PQ (voltage dependent) loads were used for load design in reference to the test system [39]. Before compensation, a steady state load flow was captured for the proposed test system. Table 3.20 shows the transmission line flows in the PSCAD/EMTDC environment and the receptive losses (50.11 MW) observed on the system. The losses (49.8 MW) are higher compared to PSS/E studies.

The variation observed is due to the loads (which vary with node voltage) and generation (which varies for terminal voltage regulation). Resultant overall losses (including transmission line losses and other major components' losses) of 53.8 MW were observed in the test system. The PSCAD/EMTDC environment (loads and voltages) are terminal voltage dependent and will change accordingly. Another noticeable issue in future compensation comparison is that load and generation values will change according to the system operating condition to maintain stability.

Table 3.20: Transmission line flows (PSCAD/EMTDC)

From Bus	P_S	Q_S	To Bus	P_R	Q_R	Loss (MW)
1	24.66	24.41	2	24.92	42.5	0.51
1	213	13.87	6	198.6	42.08	14.4
2	188.1	1.945	5	176.5	37.05	11.6
3	96.45	10.38	4(1)	95.29	19.97	1.16
3	96.45	10.38	4(2)	95.29	19.97	1.16
4	72.37	20.79	5	74.44	20.06	2.07
4	46.24	29.86	6	47.25	19.84	1.01
7	332.3	94.77	8	314.1	76.85	18.2
Total transmission loss (MW)						50.11

Table 3.21 shows an overall loss (active power) in a steady state condition as 53.8 MW. This loss includes transmission losses, transformer losses and losses from other equipment like the shunt capacitor. As discussed previously, the losses will vary with the generation and voltage of each bus.

Table 3.21: Overall loss in 12 bus system (PSCAD/EMTDC)

Generation (MW)	Load (MW)	Loss (MW)
1532.5	1478.7	53.8

According to the test system design (refer to Section 3.2), the system's major load is concentrated in area 3 and the voltage of the resultant non-generator bus (bus 4) is largely affected by the huge load. The resultant voltage at that bus is far lower than that of the other buses indicated in Table 3.22.

Table 3.22: Transmission line bus voltages (PSCAD/EMTDC)

Bus Number	**Reference voltage (kV)**	**Nominal voltage (pu)**
1	230	240.35 (1.045)
2	230	234.14 (1.018)
3	230	231.80 (1.008)
4	230	226.067 (0.9829)
5	230	232.3 (1.01)
6	230	233.2 (1.014)
7	345	362.94 (1.052)
8	345	347.76 (1.008)

As similar to PSS/E, bus 4 had a low voltage of 0.9829 pu. The bus 4 was highly affected by area 3 load and lower than system average (1.017 pu). Figure 3.15 clearly explains the trend of each bus voltage in the PSCAD environment.

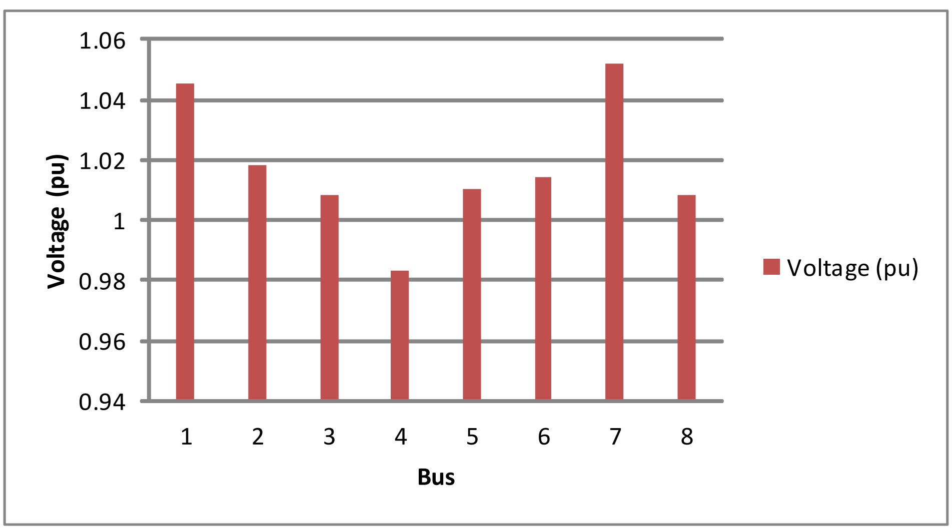


Figure 3.15: Bus voltages during steady state operation (PSCAD/EMTDC)

3.7.1 Unified Power Flow Controller (UPFC)

A unified power flow controller (UPFC) was built in PSCAD/EMTDC for compensating transmission lines. As discussed in Section 2.7, the UPFC model requires two VSC's, a transformer and a DC tie cap-bank to design the shunt and series components. The ratings of the selected device are based on the compensation or control requirements. To compensate line 7-8, a UPFC shunt part was designed with a 150 MVA transformer coupled with a 100 kV 6 pulse STATCOM. The rating of the DC capacitor connected at the terminals of the VSC was 5000 μf. For a series part with a similar rating, 3 individual (per phase) transformers were used. The resultant transmission loss observed with compensation was 53.7 MW.

Table 3.23: Overall loss with UPFC compensation

Compensated line info	**UPFC rating**	**Generation (MW)**	**Load (MW)**	**Loss (MW)**
No Compensation	No device	1532.5	1478.7	53.8
Line 7-8	Shunt Capacity=150MVA, P(Desired)=350MW, Q(Desired)=50MVAR	1533.8	1480.1	53.7
Line 3-4	Shunt Capacity=30MVA, P(Desired)=135MW, Q(Desired)=20MVAR	1548.6	1504	44.6

A 50 MVA transformers coupled, 100 kV 6 pulse STATCOM and SSSC were used in UPFC for line 3-4 compensation. The rating of the DC capacitor connected at the terminals of the VSC was 500 μf. The transmission loss observed in this compensation was 44.6 MW. Table 3.23 a similar maximum loss reduction observed in line 3-4 compensation compared to PSS/E model. It also shows that the generation required to serves the load demand in line 7-8 (1533 MW generation and 1480.1 MW load) is higher compared to line 3-4 (1548.6 MW generation and 1504 MW load) compensations.

Table 3.24: Transmission line flows (PSCAD/EMTDC) with line 7-8 Compensation

From Bus	**To Bus**	P_s	Q_s	P_r	Q_r
1	2	8.505	3.772	8.602	22.83
1	6	221.2	13.87	205.2	55.37
2	5	196.4	2.265	183.6	41.79
3	4(1)	89.09	6.696	88.1	17.7
3	4(2)	89.09	6.696	88.1	17.7
4	5	79.61	16.34	82.06	21.47
4	6	57.04	21.2	55.72	26.11
7	8	322.7	996.4	303.2	74.58

With increased power flow in system as well as STATCOM operation, the overall change in bus voltage is significant in line 3-4 compensation. To explain in detail, bus 4 voltage was improved from 0.9829 to 1.005 pu.

Table 3.25: Transmission line flows (PSCAD/EMTDC) with line 3-4 compensation

From Bus	**To Bus**	P_s	Q_s	P_r	Q_r
1	2	-20.7	17.44	20.94	-35.93
1	6	207.1	193.4	193.4	-40.72
2	5	174.5	-21.23	-164.6	39.86
3	4(1)	131.8	5.527	129.6	9.181
3	4(2)	131.8	5.527	129.6	9.181
4	5	-54.05	-32.82	55.31	-18.09
4	6	-11.02	-29.84	11.35	-26.73
7	8	345	-87.17	325.2	60.68

Table 3.26: Bus voltages with UPFC compensation

Bus	No compensation voltage (pu)	Line 7-8 Compensation voltage (pu)	Line 3-4 Compensation voltage (pu)
1	1.04	1.029	1.04
2	1.0018	1.018	1.018
3	1.008	1.008	1.007
4	.9829	.9866	1.005
5	1.01	1.008	1.045
6	1.014	1.014	1.014
7	1.052	1.019	1.041
8	1.008	1.009	1.005

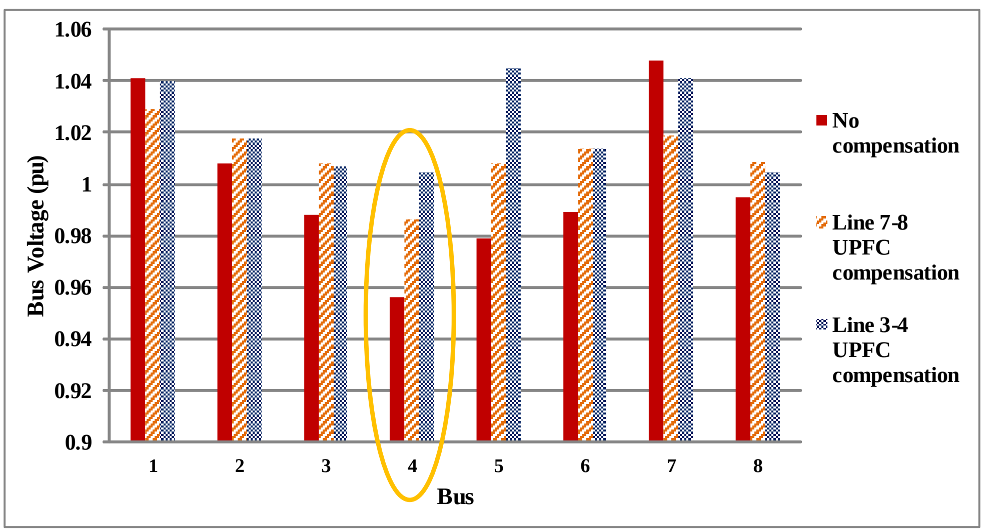


Figure 3.16: Bus voltages with UPFC compensation (PSCAD/EMTDC)

3.7.2 Sen Transformer

Utilities look for moderate response power flow controllers with less expensive, reliable and traditional operating qualities. One of the emerging devices with all the above stated qualities, the Sen Transformer(ST), was designed for testing these short line compensation. A detailed working principle of ST was explained in the previous chapter (refer to Section 2.8. Because of its recent invention and other factors, extensive controller models are not readily available in PSCAD/EMTDC, so a model with single phase units was built in PSCAD/EMTDC [28].

To build the ST, individual single phase tap setting transformers were connected in a loop as described in the construction scenario in Section 2.8. By controlling the tap settings of their transformers, the injected active or reactive power varies instantly. Based on the requirements of line 7-8 compensation, a 150 MVA Sen Transformer with a shunt-connected compensating voltage unit operating in the range of 240 to 360 degrees was used. For the other, line 3-4 compensation, a similar 60 MVA Sen Transformer with shunt-connected compensating voltage unit operating in the range of 240 to 360 degrees was used.

In the case of line 7-8 compensation, the power flow as well as the serving load increased in a similar trend, with improvement in loss reduction compared to no compensation. However, in line 3-4 compensation, the generation requirement dropped significantly (up to 10 MW) and served the load of 1475.7 MW with a higher loss reduction capacity. Table 3.27 show the generation, load and losses with each compensation.

The power flow in various transmission lines with different compensations are shown in Tables 3.28 and 3.29. Comparing both, heavily loaded line 1-6 and 2-5 are relieved (power distributed among other lines) with line 3-4 (short line) compensation.

Table 3.27: Overall loss with Sen Transformer

Line Selected	**Sen Transformer phase shift**	**Generation (MW)**	**Load (MW)**	**Loss (MW)**
No Compensation	No device	1532.5	1478.7	53.8
Line 7-8	240-360 degree phase shift	1534.6	1483	51.6
Line 3-4	240-360 degree phase shift	1527.8	1481.9	45.9

Table 3.28: Transmission line flows (PSCAD/EMTDC) with line 7-8 compensation

From Bus	**To Bus**	P_s	Q_s	P_r	Q_r
1	2	19.3	20.83	19.51	39.27
1	6	214.8	14.03	200.1	44.5
2	5	190.5	3.71	178.6	40.56
3	4(1)	97.33	4.547	96.18	14.26
3	4(2)	97.33	4.547	96.18	14.26
4	5	75.25	19.88	73.17	21.49
4	6	48.01	21.79	46.99	28.1
7	8	337.9	89.79	318.9	67.3

Table 3.29: Transmission line flows (PSCAD/EMTDC) with line 3-4 compensation

From Bus	**To Bus**	P_s	Q_s	P_r	Q_r
1	2	20.24	41.86	20.01	23.55
1	6	211	12.84	196.8	40.82
2	5	188.3	4.72	176.7	39.26
3	4(1)	93.43	3.867	96.08	12.49
3	4(2)	93.43	3.867	96.08	12.49
4	5	73.26	18.55	71.26	23.37
4	6	48.01	20.42	46.98	29.24
7	8	333.9	93.94	315.5	75.67

The overall quadrature voltage injected into the system, with the configuration of line 7-8 compensation, boosted the voltage in the system and the reflection of these voltages resulted in a slight increase in load as stated in Table 3.30.

Table 3.30: Bus voltages with Sen Transformer compensation

Bus	**No compensation voltage (pu)**	**Line 7-8 Compensation voltage (pu)**	**Line 3-4 Compensation voltage (pu)**
1	1.04	1.043	1.045
2	1.018	1.018	1.018
3	1.008	1.007	1.008
4	.9829	0.988	.9848
5	1.01	1.015	1.017
6	1.014	1.014	1.014
7	1.052	1.049	1.051
8	1.008	1.009	1.01

However, in line 3-4, bus 4 compensated voltage (0.9848 pu) is slightly lower than line

7-8 compensating voltage (0.988 pu). Overall, with the voltage comparison, the weakest bus in the system still maintained a healthy voltage with reference to the lower voltage limits. The trends of the bus voltage of each compensation method are explained in Figure 3.17. With the proposed short line compensation, a healthy voltage improvement was observed in all buses (except bus 4).

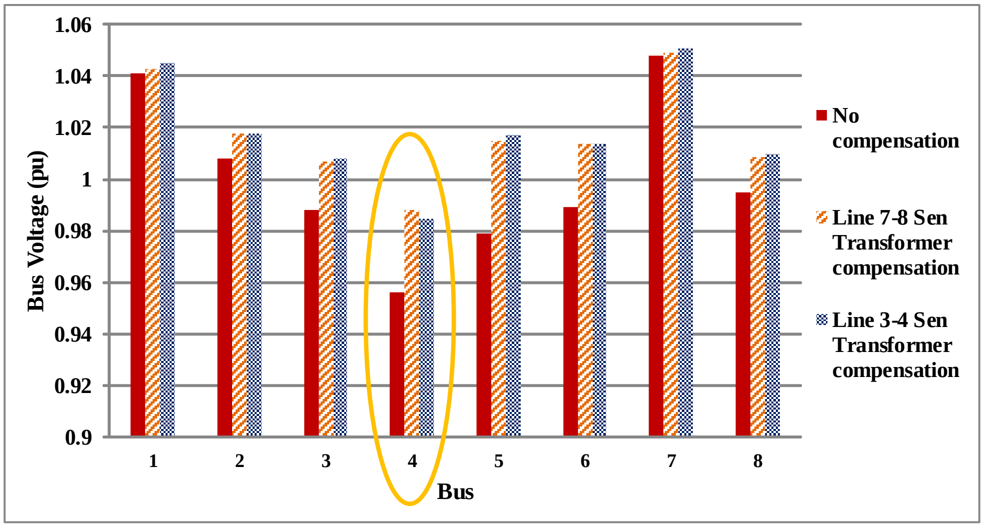


Figure 3.17: Bus voltages with Sen Transformer compensation (PSCAD/EMTDC)

3.8 Summary

This chapter evaluated the proposed short transmission line compensation with different FACTS devices. Devices from a simple low-cost Fixed Series Capacitor up to an advanced, independent control, Sen Transformer were tested in a 12 bus system. The line selection criteria results were also discussed in detail. In comparing the results, the loss minimization was found to be equal and higher in the proposed line compensation technique. Also,a better voltage regulation was observed in the majority of cases with short line optimal placement. Comparing the cost and maintenance requirement, the 3-4 location (short line) turned out to be the ideal location for relieving system stress.

Chapter 4

Conclusions

This thesis has been concerned with determining an effective way of economical power system operation as well system utilization. Advanced FACTS devices like the UPFC and the new Sen Transformer and the selection of their ideal location provide the required economy of operation along with voltage support. Hence, practical implementation of the proposed short line compensation technique will result in greater benefits to utilities while supplying cheaper power to consumers.

4.1 Summary

Losses are very common and unavoidable in electrical transmission systems. Research has been done over the past several decades to minimize these losses and researchers have come up with capacitor compensations as one of the effective ways. In the past, when the softwares were not sophisticated enough, some of the low cost devices like FSC were phiscally placed at few locations to identify the optimal location based on their size and requirements. However, in the last few decades, the massive growth of the electricity market has resulted in complicated connections, and since the new devices involve huge capital investment, so the manual testing is not considered a viable method. There are optimal power flow softwares (OPF) available to model most of these devices and do large system studies. New algorithmic and iterative approaches are used for this assessment. The focus of this thesis is to use smaller transmission lines for compensation and quantify the losses with the new low cost FACTS device (Sen Transformer) and obtain a comparison with the other commerically available FACTS devices.

Chapter 1 introduced the phenomena of losses in power systems with detailed explanations of their sources. A brief overview of voltage profile and line loading illustrates the minimum requirements in power flow regulation. Exceeding these limits will result in higher losses and will cause issues with stable operation. This section also introduced the importance of optimal location selection in placing power flow controllers and some of the requirements of the proposed approach.

Chapter 2 discussed the various power flow controllers available in the current market. The working mechanism was explained for each device, along with its modeling and respective power flow control capability. The formula were given to calculate the required injective voltage magnitudes and phase angle to meet the desired compensation. A clear separation of the results was made between series devices and shunt-series devices, and the results for each were tabulated with their respective limitations.

In Chapter 3, a test system was introduced to design and test the proposed method with the available devices. Technology advancements in FACTS provide means to regulate the transfer of more power through the desired path, and the bus voltages are also improved. The PSCAD/EMTDC model of the UPFC and the Sen Transformer confirmed their similar type of operational behaviour. Overall, the proposed method of compensating short lines resulted in a higher percentage in loss reduction compared to the traditional approach of compensating long lines.

4.2 Contribution of my research

The following are the contributions of this thesis:

• The proposed Short Line Compensation technique for compensating transmission lines. The most commonly used approach is to compensate longer transmission lines in the system but it was shown that by compensating a shortest transmission line (line 3-4 in example system) a better loss minimization could be achieved. It was also shown that the proposed approach helps in re-configuring power flow and helps in voltage profile improvement. This approach also helps in using lower rating FACTs device.

• Quantifying losses in a utility bulk network transmission system using new Sen transformer technology. The loss minimization in system is similar to UPFC device but at a cost which is a fraction of the UPFC.

4.3 Conclusions

A steady state load flow was run and the respective losses were quantified. Along with the losses, the weakest bus for the voltage and the overloaded transmission lines were also identified for required regulation.

Firstly, a simple primary power flow control device, i.e. an FSC, was designed for compensation, and the losses were quantified. reduced compared to a no compensation mode with the proposed approach. The weak bus voltage improved and their was a satisfactory voltage regulation was achieved in the overall system. Due to the limitations of FSC in controlling power flow, a transformer-based power flow regulator (PAR) was used to control the power flow. But due to its configuration, the PAR device has less capacity for minimizing losses compared to the FSC. Therefore, compensating devices with more capability must be implemented for economical operation.

Next, a Thyristor Controlled Series Capacitor was used. This is an improved version of a thyristor-based power flow controller like the TCR, TSSC etc. The resultant loss minimization of this device was similar to that of the fixed series capacitor, with additional benefits in faster operation and switching. One among them is the ability to instantly control the capacitor compensation level with thyristor firing angles. The regulation of power flow and voltage profiles follow a similar trend to that of the FSC and was improved compared to the initial case.

A PWM-based VSC was introduced for independent control of active and reactive power. The SSSC and the UPFC lowered the losses significantly. It was also noticed that the required generation to serve the load was reduced. The voltage levels were also in a healthy range compared to all other compensating devices. Subsequently, the power flow across the lines was regulated, i.e. the overloaded lines were relieved and the power flow distributed among others. The cost and maintenance requirements of VSC-based devices are high compared to other devices. To mitigate this issue and to achieve similar operational capabilities, the new Sen Transformer was studied. This device provides the required loss minimization, yet costs only about 30% of the UPFC. The voltage and line loading are improved by a significant value compared to other devices. Since they utilize a tap setting operation, Sen Transformers are slow operating devices (10 to 12 cycles) compared to UPFC devices (4 cycles). As present utilities do not require fast operating devices (minimum steady-state operating times are in the 10 cycles range), therefore the Sen Transformer is a more effective solution as a power flow controller.

In this thesis, an investigation on possible economic operation and quantification using short transmission line compensation in 12 bus test system was performed. Line 3-4 was identified as optimal location line using line stability index criteria compared to long transmission line (line 7-8) in the system. Along with economic operation, a weak bus (bus 4) voltage profile (improving from low voltage boundary) improvement was also imposed. This proposed compensation allowed the weak bus voltage go from 0.96 pu to 1.076 pu. The other devices could improve it to 0.956 pu only. Also economic dispatch and overloading relief for transmission line (lines 2-6 and 1-6) was observed in 3-12 % range.

Majority of the devices provided better loss minimization with proposed short line compensation. In case of FSC, a power savings of 2320 kW was identified when compared to long line compensation 1690 kW. The required device rating was reduced to 46.6 % when compared to long transmission line compensation (114 MVAr on line 3-4 versus 245 MVAr on line 7-8). A 2.6 million dollar savings (approximate) are possible in device cost alone. Similarly with PAR, the losses are reduced to 48.5 MW with short line compensation from 49.8 MW. The transmission losses are 2450 kW with line 3-4 compensation instead of the 2360 kW with line 7-8 compensation. The device used for short transmission line is $(\frac{1}{5})^{th}$ rating of long transmission line compensator.

The thyristor based TCSC provided an overall power savings of 2320 kW compared to line

7-8 1690 kW. Intially the overall system loss was 4,980,000 kW with no compensation, the line 3-4 compensation reduced it to 4,748,000 kW (including reduced generation kWs) compared to 4,811,000 kW (including reduced generation kWs) with line 7-8 compensation. A VSC based SSSC achieved 5300 kW loss reduction with line 7-8 compensation in comparison to line 3-4 compensation, 4000 kW loss reduction. However to achieve this level of loss reduction line 3-4 required a 53 % lower rating device compared to line 7-8 (an approximate 3.5 million dollars device installation cost saving would be achieved). In case of UPFC, loss reduction with short line 3-4 compensation achieved a overall loss reduction of 5400 kW compared to 5200 kW with line 7-8 compensation. Here 47% lower rated device was used for the compensation.

Similar to the results of UPFC, Sen Transformer provided a large percentage of loss reduction (approximately between 6-14 %). The Sen Transformer is identified as most suitable device to suppress losses, either at line 3-4 or line 7-8. By compensating short transmission line 3-4, the loss reduction is 8000 kW compared to 2200 kW with line 7-8 compensation. In addition, compensating line 3-4 provided a better voltage profile and power flow distribution among the other lines in the test system.

4.4 Future Work

Studies with an interline power flow control (IPST) for loss evaluation could be a good piece of further investigation. Furthermore, the proposed scheme could be developed as an iterative technique with security constraints.

Doing similar studies on a very large system (such as Midwest Reliability Organisation (MRO), Western Electricity Coordinating Council (WECC), and Electric Reliability Council of Texas (ERCOT) systems, which contain 10,000 or more buses) using multiple FACTS devices will be a good piece of practical research investigation for the electric utilities.

Calculating loss reduction along with stability limit evaluations with the power flow controllers as the load profile in the system changes in a 24-hour period using real time power systems simulations will be an interesting future investigation.

References

[1] “Electric power transmission and distribution losses in canada,” The world bank, Electronic data, 2010. [Online]. Available: http://data.worldbank.org/indicator/EG.ELC.LOSS.KH/countries/CA?display=graph;http://www.tradingeconomics.com/canada/electric-power-transmission-and-distribution-losses-percent-of-output-wb-data.html

[2] F.H. Branin (Jr.), “Transient analysis of lossless transmission lines,” *IEEE Proceeding*, vol. 55, no. 11, pp. 2012–2013, Nov 1967.

[3] J.A. Momoh, L.G. Dias, S.X. Guo and R. Adapa, “Economic operation and planning of multi-area interconnected power systems,” *IEEE Transactions on Power Systems*, vol. 10, no. 2, pp. 1044–1054, May 1995.

[4] L.A.S. Pilotto, and W.W. Ping, “Deretmination of needed facts controllers that increase asset utilization of power system,” *IEEE Transactions on Power Delivery*, vol. 12, no. 1, pp. 364–371, Jan 1997.

[5] D. Ghangass, *BC HYDRO - real time operation - operating order*, oo 7t-22 ed., BC Hydro, BC Hydro, 6911 Southpoint Drive, Burnaby, B.C., V3N 4X8, 27 August 2012. [Online]. Available: http://transmission.bchydro.com/nr/rdonlyres/77615f9c-d775-4ee4-8b33-b66c7b76d16e/0/7t22.pdf

[6] E.W. Kimbark, *Power System Stability*, 1995th ed., D. P. M.Anderson, Ed. WILEY-INTERSCIENCE, 1956, vol. III. [Online]. Available: http://www.scribd.com/doc/54952495/8/STEADY-STATE-STABILITY

[7] System Planning, *SASKPOWER open access transmission tariff*, SaskPower, 2025 Victoria Ave Regina, SK S4P 0S1, September 1 2011. [Online]. Available: http://www.saskpower.com/wp-content/uploads/open_access_transmission_tariff.pdf

[8] G. Stephane, S.C. Rachid, and J.G. Alain, "Optimal location of facts devices to enhance power system security," in *2003 IEEE Bologna Power Tech Conference Proceedings*, vol. 3, 23-26 June 2003.

[9] M. Moghavvemi, and O. Faruque, "Real-time contingency evaluation and ranking technique," *IEE Proceeding on Generation, Transmission and Distribution*, vol. 1350-2360, pp. 517–524, Sep 1998.

[10] A. A. A. Esmin, G. Lambert-Torres, and Antnio C. Zambroni de Souza, "A hybrid particle swarm optimization applied to loss power minimization," *IEEE Transaction on Power systems*, vol. 20, no. 2, pp. 859–867, May 2005.

[11] M.H. Haque, "Capacitor placement in radial distribution systems for loss reduction," *IEE*, vol. 146, no. 5, pp. 501–505, Sep 1999.

[12] S.A. Jumaat, I. Musirin, M.M. Othman, and H. Mokhlis, "Placement and sizing of thyristor controlled series compensator using pso based technique for loss minimization," in *2012 IEEE International Power Engineering and Optimization Conference (PEOCO2012)*. Melaka, Malaysia: IEEE, 6-7 June 2012, pp. 285–290.

[13] E. J. de Oliveira, J. W. Mnrangon Lima, and K. C. de Almeida, "Allocation of facts devices in hydrothermal systems," *IEEE Transaction on Power System*, vol. 15, no. 1, pp. 276–282, Feb 2000.

[14] M. Tripathy, S. Mishra, L. L. Lai, and Q. P. Zhang, "Transmission loss reduction based on facts and bacteria foraging algorithm," in *Parallel Problem Solving from Nature - PPSN IX*, S. Link, Ed., vol. 4193. 9th International Conference, Reykjavik, Iceland: Springer Link, September 9-13 September 9-13, 2006, pp. 222–231.

[15] Joong-Rin Shin, Byung-Seop Kim, Jong-Bae Park, and K.Y. Lee, "A new optimal routing algorithm for loss minimization and voltage stability improvement in radial power systems," *IEEE Transaction on Power System*, vol. 22, no. 2, pp. 648–657, May 2007.

[16] Sang-Joong Lee, "Location of a superconducting device in a power grid for system loss minimization using loss sensitivity," *IEEE Transactions on Applied Superconductivity*, vol. 17, no. 2, pp. 2351–2354, June 2007.

[17] G.K. Viswanadha Raju, and P.R. Bijwe, "An efficient algorithm for minimum loss reconfiguration of distribution system based on sensitivity and heuristics," *IEEE Transaction on Power System*, vol. 23, no. 3, pp. 1280–1287, Aug 2008.

[18] M.A. Sayed, and T. Takeshita, "All nodes voltage regulation and line loss minimization in loop distribution systems using upfc," in *IEEE Energy Conversion Congress and Exposition (ECCE).* San Jose, CA, USA: IEEE, 20-24 Sept 2009, pp. 2719–2726.

[19] A. Naresh, Sode-Yome Arthit, Mithulananthan, and Nadarajah, "Facts about flexible ac transmission systems (facts) controllers: Practical installations and benefits," in *Proceedings of Australian Universities Power Engineering Conference (AUPEC)*, vol. 2. Hobart, Tasmania, Australia: School of Engineering, University of Tasmania, September 25-28 2005, pp. 184–190. [Online]. Available: http://itee.uq.edu.au/~aupec/aupec05/AUPEC2005Proceedings.html

[20] S. Ghosh, S.P. Ghoshal, and S. Ghosh, "Optimal sizing and placement of distributed generation in a network system," *International Journal of Electrical Power & Energy Systems*, vol. 32, no. 8, pp. 849–856, Oct 2010. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0142061510000384

[21] N.G. Hingorani, "Facts technology state of the art, current challenges and the future prospects," *IEEE Power Engineering Society General Meeting, Tampa, Florida*, pp. 1–4, 24-28 June 2007.

[22] K.R.C. Mamandur, and R.D. Chenoweth, "Optimal control of reactive power flow for improvements in voltage profiles and for real power loss minimization," *IEEE Transaction on Power apparatus and systems*, vol. PAS-100, no. 7, pp. 3185–3194, July 1981.

[23] S. Biansoongnern, S. Chusanapiputt, S. Phoomvuthisarn, Chusanapiputt, and Phoomvuthisarn, "Optimal svc and tcsc placement for minimization of transmission losses," in *International Conference on Power System Technology*, 2006, pp. 1–5.

[24] G. Reed, R. Pape, and M. Takeda, "Advantages of voltage sourced converter (vsc) based design concepts for facts and hvdc-link applications," *IEEE Power Engineering Society General Meeting*, vol. 3, 13-17 July 2003.

[25] H.F. Wang, "Applications of modelling upfc into multi-machine power systems," *IEE Proceeding on Generation, Transmission and Distribution*, vol. 146, no. 3, pp. 306–312, May 1999.

[26] J.F. Keri Albert, M.A.S. Ben, Lombard Xavier, and A. Eiriachy, "Unified power flow controller (upfc): modeling and analysis," *IEEE Transaction on Power Delivery*, vol. 14, no. 2, pp. 684–654, Apr 1999.

[27] K.K. Sen, "Comparison of the "sen" transformer with the unified power flow controller," *IEEE Transaction on Power Delivery*, vol. 18, no. 4, pp. 1523–1533, Oct 2003.

[28] B. Asghari, M.O.O. Faruque, and V. Dinavahi, "Detailed real-time transient model of the sen transformer," *IEEE Transaction on Power Delivery*, vol. 23, no. 3, pp. 1513–1521, june 2008.

[29] K.K. Sen, and M.L. Sen, *Introduction to FACTS Controllers: Theory, Modeling, and Applications*, I. P. E. Board, Ed. 445 Hoes Lane, Piscataway, NJ 08855: John Wiley & Sons, Oct 2009.

[30] J.W. Butler, "Capacitors and circuit performance," *Electrical Engineering (IEEE)*, vol. 60, pp. 408–415, June 1941.

[31] O.C. Parks, A.A. Girgis, and M.E. Frick, "Simulating ferroresonance in a series compensated distribution network," in *Ninth International Conference on Harmonics and Quality of Power*, IEEE, Ed., vol. 1, Orlando, FL, USA, 1-4 Oct 2000, pp. 162–167.

[32] M.A. Ibrahim, "Phase angle regulating transformer protection," *IEEE Transaction on Power Delivery*, vol. 9, no. 1, pp. 394–404, Jan 1994.

[33] W.D. Stevenson, *Elements of power system analysis*. Mc Graw-Hill, 1982.

[34] K.K. Sen, and M.L. Sen, *Introduction to FACTS Controllers: Theory, Modeling, and Applications*. Hoboken, New Jersey: John Wiley & Sons,Inc., 2009.

[35] S. Meikandasivam, R.K. Nema, and S.K. Jain, "Selection of tcsc parameters: Capacitor and inductor," in *2010 India International Conference on Power Electronics (IICPE)*. New Delhi, India: IEEE, 28- 30 Jan 2011, pp. 1–5.

[36] [Online]. Available: http://www.siemens.co.in/pool/about_us/our_business_segments/facts_catalog.pdf

[37] Jang-Hwan Kim, and Seung-Ki Sul, "A carrier-based pwm method for three-phase four-leg voltage source converters," *IEEE Transaction on Power Electronics*, pp. 66–75, Jan 2004.

[38] L. Gyugyi, C.D. Schauder, and K.K. Sen, "Static synchronous series compensator: a solid-state approach to the series compensation of transmission lines," *IEEE Transaction on Power Delivery*, vol. 12, pp. 406–417, Jan 1997.

[39] S. Jiang, U.D. Annakkage,and A.M. Gole, "A platform for validation of facts models," *IEEE Transaction on Power Delivery*, vol. 21, no. 1, pp. 484–491, Jan 2006.

[40] E. Balagurusamy, *Numerical Methods*, 25th ed., T. M. Hill, Ed. Tata McGraw Hill, 1999.

[41] P. Kundur, Neal J. Balu, and Mark G. Lauby, *Power system stability and control*, McGraw-Hill, Ed. McGraw-Hill, 1994.

Appendix A

IEEE 12 Bus System

A.1 IEEE 12 Bus System generator parameters

Table A.1: Machine and system data

Hydro Generator data (G2)	$490MW, 185MVAR$, $22kV$, $r_a = 0.0002p.u.$, $x_l = 0.012p.u.$, $x_d = 1.5p.u.$, $x_q = 1.2p.u.$, $x'_d = 0.4p.u.$, $x''_d = 0.35p.u.$, $x''_q = 0.35p.u.$, $T'_{d0} = 5s$, $T''_{d0} = 0.02s$, $T''_{q0} = 0.02s$, $H(Gen1) = 5.0s$
Thermal Generator data (G3)	$178MW, 0MVAR$, $22kV$, $r_a = .0002p.u.$, $x_l = .01p.u.$, $x_d = 1.4p.u.$, $x_q = 1.35p.u.$, $x'_d = 0.3p.u.$, $x''_d = 0.28p.u.$, $x''_q = 0.27p.u.$, $T'_{d0} = 6s$, $T''_{d0} = 0.002s$, $T''_{q0} = 0.002s$, $H(Gen1) = 3.0s$
Thermal Generator data (G4)	$178MW, 0MVAR$, $22kV$, $r_a = .0002p.u.$, $x_l = .01p.u.$, $x_d = 1.5p.u.$, $x_q = 1.2p.u.$, $x'_d = 0.4p.u.$, $x''_d = 0.28p.u.$, $x''_q = 0.27p.u.$, $T'_{d0} = 5s$, $T''_{d0} = 0.002s$, $T''_{q0} = 0.002s$, $H(Gen1) = 5.0s$

Table A.2: Bus data

Bus	**Bus Data**				
	Nominal voltage (kV)	**Specified kV (pu)**	**Load (MVA)**	**Shunt (MVAr)**	**Generation (MW)**
1	230				
2	230		280+j200		
3	230		320+j240		
4	230		320+j240	160	
5	230		100+j60	80	
6	230		440+j300	180	
7	230				
8	345				
9	22	1.04			
10	22	1.02			500
11	22	1.01			200
12	22	1.02			300

Table A.3: Transformer data

From-to	**Volatge kV**	**Leakage reactance (pu)**	**Rating (MVA)**
1-7	230-345	0.01	1000
1-9	230-22	0.01	1000
2-10	230-22	0.01	1000
3-8	230-345	0.01	1000
3-11	230-22	0.01	1000
6-12	230-22	0.02	500

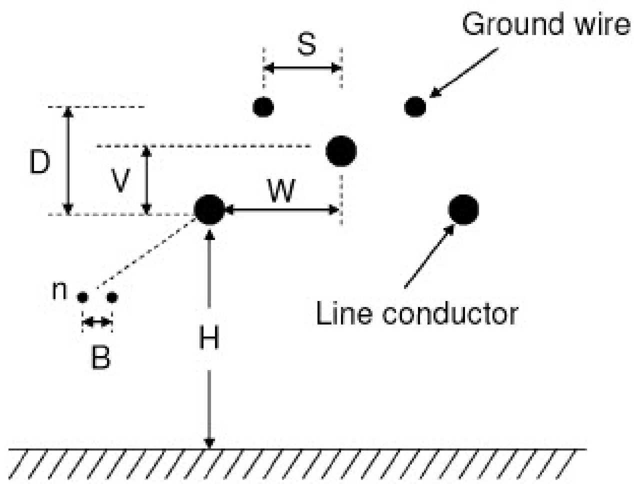


Figure A.1: Transmission line configuration

Table A.4: Transmission line configuration parameters

Line Pramaters	**230 kV line**	**345 kV Line**
Voltage	230	345
structure type	3H6	3H6
H(m)	14.4	17.526
V(m)	1.22	3.505
W(m)	5.49	7.925
Sag	5.94	7.254
n(conductor/bundle)	1	2
B (m)	0.4572	0.4572
Conductor type	954ACSR 54/7	795ACSR 26/19
DC resistance (ohms/km)	0.0587	0.0683
Ground wires	2	2
S(m)	3.05	4.648
D(m)	3.81	5.00
Ground resistivity (ohm*m)	100	100
Sag of GW (m)	4.45	7.254

Table A.5: Line data (100 MVA base)

Line Data							
From Bus	**To Bus**	**Voltage (kV)**	**Length (km)**	**R**	**X**	**B**	**Rating (MVA)**
1	2	230	100	0.01144	0.09111	0.18261	250
1	6	230	300	0.03356	0.26656	0.55477	250
2	5	230	300	0.03356	0.26656	0.55477	250
3	4(1)	230	100	0.01144	0.09111	0.18261	250
3	4(2)	230	100	0.01144	0.09111	0.18261	250
4	5	230	300	0.03356	0.26656	0.55477	250
4	6	230	300	0.03356	0.26656	0.55477	250
7	8	345	600	0.01595	0.17214	3.28530	500