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Θέμα

«UPGRADING A DISTRIBUTION SYSTEM WITH D-FACTS DEVICES: THE IMPACT ON VOLTAGE PROFILE, SYSTEM LOSSES AND EXPECTED FAULT CURRENTS»

Επιβλέπων
ΠΑΝΑΓΗΣ ΒΟΒΟΣ (ΛΕΚΤΟΡΑΣ)

Αριθμός Διπλωματικής Εργασίας: 1050298/2016

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Πιστοποιείται ότι η Διπλωματική Εργασία με θέμα

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Του φοιτητή του Τμήματος Ηλεκτρολόγων Μηχανικών και Τεχνολογίας Υπολογιστών

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Φοιτητής: SUHAIL AFZAL Επιβλέπων: ΠΑΝΑΓΗΣ ΒΟΒΟΣ

Περίληψη (ABSTRACT)

The continuous growth of demand and the dispersed nature of most new generation create a number of challenges for modern Power Systems like dynamic stability, line limit utilization, power sharing between different areas and reliability. Bus voltage magnitude is an important parameter for the quality of a power system and it is related to the flow of reactive power across the lines. Bus voltage magnitude is in direct relationship with the demand of reactive power. Decrease in bus voltages below the minimum threshold of nominal voltage range may cause voltage collapse and increase in bus voltage beyond the maximum threshold may lead to black out. The smaller the deviation of bus voltages from nominal, the more stable the power system will be.

This research has been carried out with the goals of improving voltage profile of the system buses, decreasing system losses and limiting line fault currents. Distributed Flexible AC Transmission System Controllers (D-FACTS) are among those devices that can provide series compensation to the power system. To achieve the goals, Distributed Thyristor Controlled Series Capacitor Device (D-TCSC) has been utilized to provide series compensation to the network because of their simple structure, low cost, quick response and communication capability. Mathematical model of the device has been incorporated in the power flow equations by introducing new variables having lower and upper bounds based on the levels of capacitive and inductive compensations those can be provided by these series

controllers. The Matpower/Matlab platform has been used for formulation of power flow equations and to calculate the gradients of equality and inequality nonlinear constraints. Objective function is formulated considering the total cost of power generation and the cost of these devices. Knitro optimizer has been utilized to find the optimal power flow solution. Further to this work, Fault Limit Constraint on a transmission line has also been incorporated in power flow as a new nonlinear constraint to find the optimal values for inductive compensation those satisfy the set fault constraint.

The methodology has been tested on IEEE 06-Bus and 30-Bus power systems. In both cases, improvement in voltage profile has been observed. Reactive power line losses are reduced significantly whereas active power dissipation across the lines remained same causing decrease in total MVA generation of generating units. Some increase in line limit utilization of few lines has been observed; however, in general the average line utilization of the network has been reduced. Moreover, the set fault limit constraint has been respected with successful convergence to the optimal solution.

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1 CHAPTER

1.1 INTRODUCTION

Existing power systems are in more stressful conditions nowadays due to urbanization and decentralization of energy generation after the invention of new resources of energy generation like renewables. Power systems are facing problems of congestion, instability and integration of energy generated from different renewable resources at different voltage levels. Among these issues voltage stability is one of the most important quality indexes of a power system. One of the causes of voltage instability is demand of reactive power. Voltage declines in case of increase in reactive power demand and vice versa. Voltage collapse may occur in case buses are being operated at lower voltage levels and black out may result if buses are being operated at higher voltage levels. So, voltage level of all the system buses should neither decrease nor increase from the pre-defined limits to avoid both of the above mentioned cases. Reactive power support must be provided to the power system in order to avoid any such disaster or failure.

Flexible AC Transmission System (FACTS) controllers, among other, can provide series compensation, shunt compensation and hybrid compensation. Whereas, Distributed Flexible AC Transmission System (D-FACTS) controllers can only provide series compensation but with remarkable advantages over conventional FACTS controllers. A common category of such devices are Thyristor controlled devices, where compensation is provided as a function of the firing angle of the Thyristor. So by selecting suitable firing angle, reasonable amount of compensation can be provided to the power system. Thyristor Controlled Series Capacitor (TCSC) from the group of FACTS controllers and Distributed Static Series Compensator (DSSC), also known as Distributed Thyristor Controlled Series Capacitor (D-TCSC), from the group of D-FACTS controllers are one of those devices that can provide series compensation.

Mathematically, power flow problems are nonlinear problems bounded by equality and inequality constraints. Different numerical methods are available to solve such type of problems like Newton-Raphson, Gauss-Siedal, fast decoupled etc., all iterative. Different commercial and research tools are available to solve such type of complex problems like

Matlab, PSAT, and Matpower etc.

Exchange of active and reactive powers between two buses are in inverse relationship with impedance of power line connecting those buses. By adding a TCSC or D-TCSC device in a branch line, reactance of the line can be made variable that can be controlled within defined lower and upper bounds simply by controlling the firing angle of the Thyristor. In a mathematical sense, reactance parameter of a certain branch where device is to be installed can be visualized as a new variable that can be included in the formulation of power flow equations of a power system. So, by changing the value of this variable we can indirectly control the power flow through that line. Hence optimal power flow can be executed to find out the optimal value of this variable. That will not only provide the optimal size of the device that should be installed in that line but also the optimal value of compensation required from the installed device.

To meet this objective, branch reactance parameters of the branches where D-TCSCs or TCSCs devices are supposed to be installed are defined as new nonlinear variables. These new variables are created and included in power flow equations. Lower and upper bounds are defined on each variable that are to match the practical level of compensation that can be provided by these devices in capacitive and inductive mode of operation. Further, gradients of equality and inequality constraints have been calculated to make optimizer more robust and fast while solving this nonlinear problem. The methodology has been used on IEEE 06-Bus and 30-Bus power systems. These systems are not only simple enough so that the results can be interpreted by experience but they are also of a good size to prove the applicability of the approach on real systems. The formulation of power flow and calculation of gradients has been done by using Matpower [18] and Knitro [19] has been used as an optimizer tool.

The results of optimal power flow for both cases have been presented, discussed and analyzed in this thesis. A significant improvement in voltage profile has been achieved. Voltage magnitude of busses for all test scenarios is found within the range of ±2% from the nominal voltage magnitude. Reactive power line losses of the power system also reduced significantly with a prominent decrease in reactive power generation of the generators. Whereas almost no reduction in active power line losses has been observed and so overall generation of active power is same even after addition of Distributed Thyristor Controlled Series Capacitor devices.

Taking advantage of the inductive compensation provided by this device, fault limit constraint has also been introduced on a line to limit the fault current through that line below the set threshold. The results has been presented for 06-Bus System with successful convergence to the optimal solution that provides optimal value for inductive compensation required to respect the set fault limit constraint.

Furthermore, it has been found that the proposed methodology is not only more efficient and robust as gradients have been provided for constraints but more flexible as code can be modified easily and third party optimizer tools can also be used for the optimization purpose.

2 CHAPTER

2.1 LITERATURE REVIEW

2.1.1 Problems of Power Systems

Nowadays power systems are facing more challenges and are under more stressful conditions due to factors like overexploitation of existing transmission systems, the limited number of new power station projects, and new regulations, etc. This causes reliability and security problems of system operation. Stability of bus Voltages is one of these concerns. Voltage stability is referred as the ability of a power system to maintain steady voltages at all of its buses subject to a disturbance from a given initial operating condition. It is in connection with the ability to maintain and restore equilibrium between demand of load and supply from the power system. This disturbance in equilibrium between demand and supply may causes instabilities that may occur in the form of a progressive rise or fall of voltages in some buses. A possible outcome of this instability in voltage is loss of load in an area, tripping of lines and other elements of protective system that finally leads to cascading outages. Loss in synchronization of some generators may result from these outages or from operating conditions that violate field current limits. [1]

Instability of voltage can be classified into two categories: large-disturbance and small-disturbance. Large-disturbance is defined as the ability of system to maintain steady voltages even after occurrence of large disturbances in the power system like system fault, loss of generation, or circuit contingencies whereas the small-disturbance refers to the ability of system to maintain steady voltages in case of small perturbations such as an increase or a decrease in system load. The small-disturbance voltage stability is mainly related to reactive power imbalance. This imbalance mainly occurs on a local network or a specific bus in a power system. If a local network has a shortage of reactive power, the voltage in the network will decrease and may be lower than the minimum threshold of normal voltage range. It may lead to voltage collapse in the worst situation. In case, the reactive power on a local network exceeds the necessary level, it will increase voltage in the network. It may even grow higher than that of maximum threshold of voltage and may cause black out in worst scenario. Both of these situations need to be avoided in the operation of power systems to prevent any disaster.

The bus voltage is one of the most important service quality and security indices of a power system. In general, the desired bus voltage magnitude is about 1.0 pu. Voltage will be more stable when the term ($|V_i - 1|$) is smaller, where V_i is the voltage magnitude of *ith* bus. To achieve this small difference in values, a reactive power support must be provided to the network. [2]

2.1.2 Power Flow Control

In a power system the flow of active and reactive power between two buses can be calculated as below: [3]

$$P_{12} = \frac{V_1 V_2}{X_{12}} Sin\theta_{12} \qquad \textit{Equation 1}$$

$$Q_{12} = \frac{V_1^2}{X_{12}} - \frac{V_1 V_2}{X_{12}} Cos\theta_{12} \qquad \textit{Equation 2}$$

P_{12} and Q_{12} represents active and reactive power flows respectively from bus 1 to bus 2. V_1 and V_2 represents phase voltage rms value, X_{12} is the transmission line impedance and θ_{12} is the difference in voltage phase angles. It can be seen from these equations that power flow between two buses can be controlled by changing bus voltages, line impedance and phase difference. FACTS controllers and D-FACTS controllers are the devices that can be used for this purpose.

2.1.3 FACTS Controllers

Flexible AC Transmission System (*FACTS*) controllers can increase or decrease reactive power according to the demand of the network to improve the loadability of power system, reduce system loss, and also improve the voltage profile of power system. The variables and parameter of the transmission line that can be controlled by these FACTS controllers in an effective and fast way are voltage angles, voltages amplitudes and line impedance.

FACTS technology can provide power systems with both parallel and series compensation. The general problems of the power systems that can be solved by FACTS controllers are congestion of transmission lines, inter-area and local power oscillations, flicker, voltage imbalance and voltage variations at different load conditions, reactive power balancing, high short-circuit currents and voltage as well as phase-angle in stabilities. The most common application of series compensation is FSC (Fixed Series Capacitor), TCSC (Thyristor Controlled Series Capacitor), TPSC (Thyristor Protected Series Capacitor) and FSR (Fixed Series Reactor). For parallel compensation, MSC (Mechanically Switched Capacitor), MSR (Mechanically Switched Reactor), MSCDN (Mechanically Switched Capacitor with Damping Network), SVC and SVC PLUS are frequently used. [4] For hybrid compensation, Dynamic Power Flow Controllers (DFC) and Unified Power Flow Controllers (UPFC) are among those devices.

2.1.4 Structure of TCSC

Thyristor Controlled Series Capacitors (*TCSC*) is one of the FACTS devices that can provide series compensation. Physical structure and equivalent circuit of the device are shown in Figure 1 and Figure 2. It uses an extremely simple main circuit. In this FACTS device a capacitor is inserted directly in series with the transmission line to be compensated and a Thyristor-controlled inductor is connected directly in parallel with the capacitor, thus no interfacing equipment, like high voltage transformers, are required. This makes the TCSC much more economic than some other competing FACTS technologies. Thyristor controlled series capacitor is a device that is having a fixed value capacitor shunted by a Metal Oxide Varistor (MOV) and a Thyristor controlled Reactor (TCR). Metal Oxide Varistor is connected in parallel to protect capacitor from over voltages and to keep capacitor in the circuit during the fault condition to provide transient stability. [5]

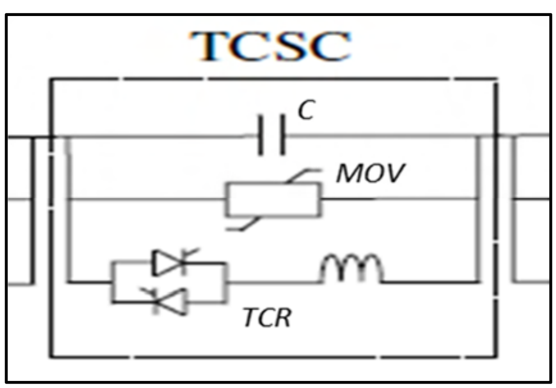


Figure 1 Physical Structure of TCSC [5]

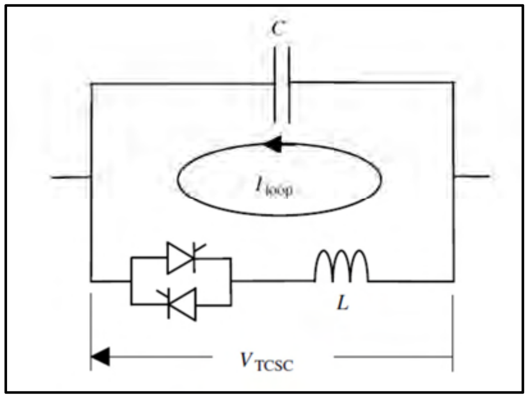


Figure 2 Equivalent Circuit of TCSC [5]

Thyristor controlled series capacitor is having three different modes of operation. Those are known as Thyristor Switched Reactor (TSR), Thyristor Blocked Mode (TBM) and Waiting Mode (WTM). These modes of operation can be selected through operation mode selection logic. In TSR mode, the capacitor is parallelized with the reactor and TCSC changes from capacitive to inductive:

$$X_{TSR} = \frac{jX_c X_L}{X_c - X_L} \qquad \textit{Equation 3}$$

Where X_C = Capacitor Reactance

X_L = Inductor Reactance

In Thyristor Blocked Mode (TBM), firing system is blocked meaning that TCSC will be in capacitive mode.

$$X_{TCSC} = X_C \qquad \textit{Equation 4}$$

In Waiting Mode, TCSC waits with a fixed firing angle for a certain time until a new mode of operation is set.

Generally TCSC equivalent reactance is a function of its capacitive and inductive parameters and the angle of firing. This relationship can be expressed by Equation 5 and is shown in Figure 3. [5]

$$X_{TCSC}(1) = -X_c + C_1\{2(\pi-\alpha) + Sin[2(\pi-\alpha)]\} + C_2 Cos^2(\pi-\alpha)\{\omega\, tan[\omega(\pi-\alpha)] - tan(\pi-\alpha)\} \qquad \textit{Equation 5}$$

Where:

$$X_{LC} = \frac{X_C X_L}{X_C - X_L}$$

$$C_1 = \frac{X_C + X_{LC}}{\pi}$$

$$C_2 = -\frac{4X_{LC}^2}{X_L \pi}$$

The poles of this equation are:

$$\alpha = \pi - \frac{(2n-1)(LC)^{\frac{1}{2}}\pi\omega}{2}, for\ n = 1,2,3 \ldots\ldots \qquad \textit{Equation 6}$$

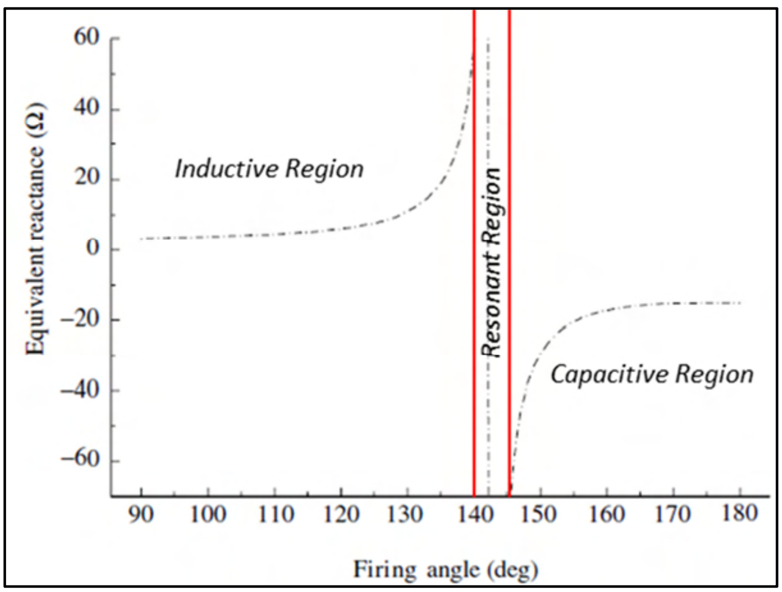


Figure 3 Thyristor Controlled Series Capacitor Fundamental Frequency Impedance [5]

2.1.5 D-FACTS Controllers

Distributed Flexible AC Transmission System Controllers (*D-FACTS*) are devices that can provide series compensation to the power network. High cost and reliability problem of FACTS controllers lead to the idea of distributed controllers. While deploying FACTS controllers, considering the safety factor and future demand may result in the installation of high rating device that is too expensive and needs huge investment cost. Further, the installation of FACTS controllers may cause a single point failure. Whereas D-FACTS are the devices that are installed in a distributed manner on a transmission line as shown in Figure 4. So there is no risk of single point failure. Moreover, with growing demand of power, new devices can be added to the same power line in future. Distributed Static Series Compensator (DSSC) and Distributed Series Reactor (DSR) are among D-FACTS controllers that can provide series compensation [6].

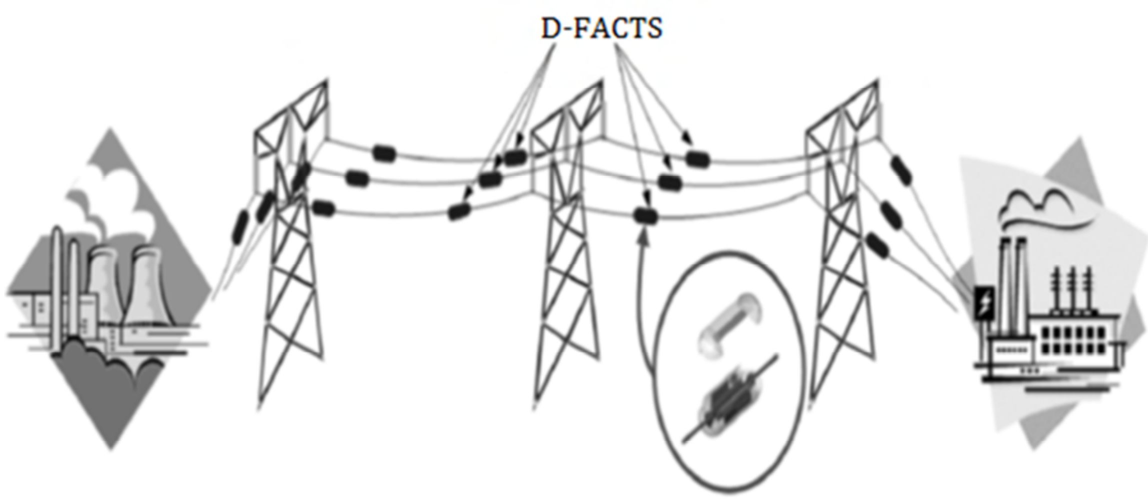


Figure 4 D-FACTS Modules on Power Lines [7]

2.1.6 Structure of D-TCSC

Distributed Static Series Compensator (DSSC), also known as Distributed Thyristor Controlled Series Capacitor (D-TCSC), is one of the D-FACTS controllers that can inject variable reactance in a power line. D-TCSC is able to inject capacitive as well as inductive reactance in the transmission line. Circuit schematic of D-TCSC is shown in Figure 5. The device consist of a single turn transformer (STT) and single phase inverter of rating ~ 10 KVA. The device is also equipped with communication module hence can be communicated through power line carrier (PLC) or wireless network. Power is fed to the associated control circuit by the local power supply module avail in the package [8].

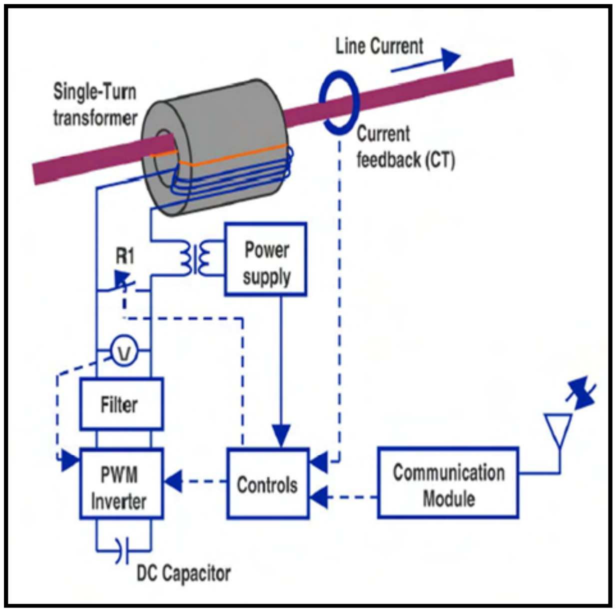


Figure 5 Circuit Schematic of D-TCSC [8]

Controller unit of D-TCSC is shown in Figure 6. It can be seen that the device is equipped with three switches that are being controlled by the control module. The single turn transformer (STT) injects quadrature voltage in the power line depending upon the value of reactance that can be positive or negative. Quadrature voltage can be controlled autonomously by the control unit or can be set by the system operator through communication module.

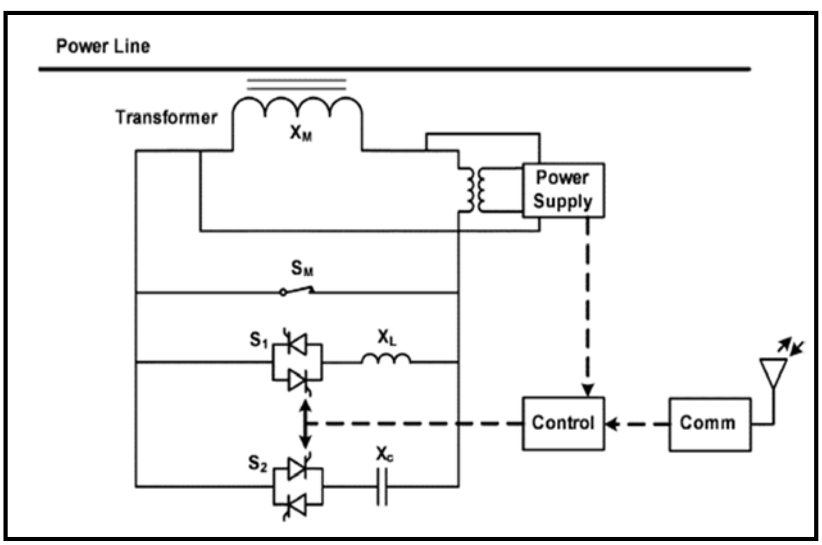


Figure 6 Controller Unit of D-TCSC [6]

Furthermore, the D-TCSC device is lesser in weight and has a clamp on capability. So the device can either be clamped on power line or can be connected between power lines through its end supports. Clamp on capability of the device is shown in Figure 7 [8].

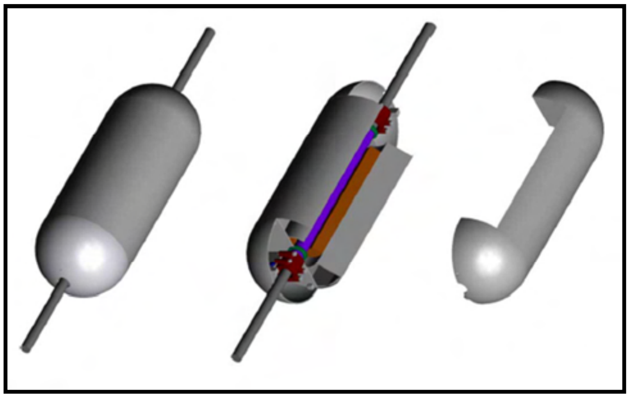


Figure 7 Clamp-on Capability of D-TCSC

2.1.7 Existing Solutions

Location for the placement of device, size of the device and number of devices to be placed in a network are the areas being focused in research. Multi objective functions have been formulated and minimized by using different optimization techniques for obtaining the optimal solutions to find location, type and value of FACTS controllers. Different algorithms for optimization of these multi objective functions have been proposed in the literature. Few are gradient techniques, harmony method of optimization, swarm optimization technique and ant optimization approach etc. For the formulation of these multi objective functions, different parameters of a power system have been taken into consideration by the researchers. The active power transmission loss, the performance index of active power flow and the performance index of the voltage difference between buses have been considered in objective function of [2] to find the type, location and value of FACTS devices. Total cost of active power generation of all generators, the power loss of transmission lines, System Loadability and cost of installation of FACTS controllers normalize over a period of 5 years have been proposed in [9] to find optimal number, location and settings of FACTS controllers used. Static Var Compensator (SVC) and Thyristor Controlled Series Capacitor (TCSC) have been modeled as shunt load and series reactance in [10] using PSAT and objective function that is sum of overall generation cost, investment cost of both FACTS controllers and total system loss has been minimized. Objective function in [11] has been mathematically modeled by considering cost of generation, installation cost of shunt controller, total real power loss and voltage deviation. Objective function considered in [12] minimizes the cost of generation of active and reactive powers by considering the cost of FACTS normalized by a payback period.

2.1.8 Proposed Solution

In a power system, the lines are selected on the basis of reactive power loss dissipation. D-TCSC devices may also be inserted in those lines. The reactance of these lines is inserted as a variable in the formulation of power flow equations using Matpower. Lower and upper limits are set to the reactance of these lines where Distributed Thyristor Controlled Series devices have been added. In the objective function, cost of these devices has been considered along with the cost of generation. Gradients of equality and inequality nonlinear constraints have been calculated to help optimizer in finding optimal solution. The objective function has been minimized by finding a feasible optimal solution using Knitro optimizer tool. In this way, optimal value of compensation required for certain lines are found and by analyzing the results of optimal power flow for 06-Bus and 30-Bus power systems, it has been proved that voltage profile of the power system can be improved with significant reduction in reactive power losses at the same time.

Moreover, by taking advantage of the fact that both capacitive and inductive compensation can be provided by these devices, fault current constraint has been introduced in the power flow equations and optimum value for the inductive compensation has been found out for the power system that can decrease the current through the line during fault conditions. The fact has been proved by the results of 06-Bus power system.

2.1.9 Pros and Cons of D-TCSCs

Distributed Thyristor Controlled Series Capacitor device has been chosen because of its communication capability, fast control response and ability to efficiently increase loadability [13]. It also has the ability for elimination of sub synchronous resonance risks and damping of active power oscillations. The device can provide post-contingency stability improvement as well as dynamic power flow control [14]. The device can be installed in distributed manner. Thyristor Controlled Reactor harmonic currents are trapped inside the device due to low internal impedance as compared to network impedance while in Static VAR Compensators these harmonic currents are escaped in the network. [5] Due to simple structure and construction the cost of installation for this device is low as compared to other FACTS controllers like Static VAR Compensators and Unified Power Flow Controllers. There is also an incentive for operating this device in its inductive mode at minimum load condition when bus voltages have a tendency to increase e.g. over night.

However the use of D-TCSC in a power system has some disadvantages as well. This may add additional losses in the network in the form of switching losses of the device. The switching loss of the device can be found out from the approximation of resistance (*R*) being presented at each level of compensation provided. *R* of the device can be approximated as $\%0.2X_{TCSC}$ to $\%0.4X_{TCSC}$. [15] Moreover the bulk amount of investment cost and extra installation and maintenance burden of the device can be some of its disadvantages.

3 CHAPTER

3.1 METHODOLOGY

3.1.1 Mathematical Modeling

A Distributed Thyristor Controlled Series Capacitor (D-TCSC) consists of a thyristor controlled capacitor (TCC) and a Thyristor controlled reactor (TCR) in parallel as shown in Figure 8. This device provides a smooth variation from capacitive to inductive mode. The reactance of the device is a function of the firing angle of thyristors. Depending upon the angle of firing, the device can be set either into inductive mode or capacitive mode.

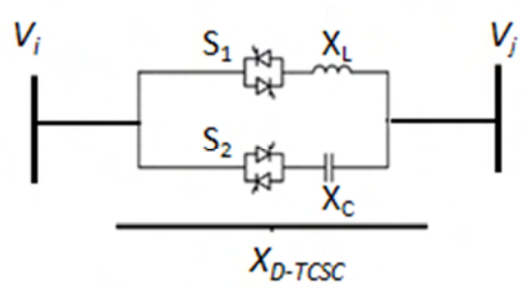


Figure 8 TCSC Comprising a Capacitor and a TCR in Parallel

So a D-TCSC can be considered as a variable reactance in series with a transmission line. The model of a transmission line with installed D-TCSC is shown in Figure 9 where $X_{D\text{-}TCSC}$ is the variable reactance of D-TCSC and Z_{Line} is the reactance of power line connecting bus i with bus j.

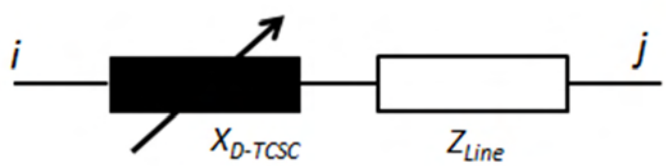


Figure 9 Transmission Line Model with TCSC

The transmission line and the power flow at the ends of line after adding D-TCSC device is shown in Figure 10.The line impedance after adding D-TCSC can be represented by Z_{ij} that is composed of both resistive and reactive component of the said transmission line.

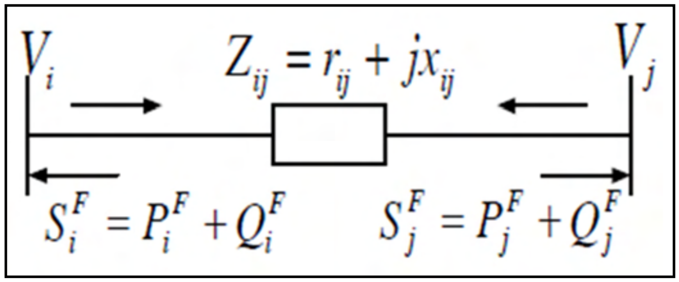


Figure 10 Power Flow at the Ends of Line [16]

Reactance of transmission line is now the sum of the actual reactance of transmission line and the compensated reactance that has been introduced through the use of D-TCSC. The reactance that can be inserted by controlling D-TCSC is related to the compensation factor rtcsc of the device. To be more realistic, this compensation factor has been considered from -0.7 to 0.2 for this research to avoid over compensation [17].

$$X_{ij} = X_{Line} + X_{D-TCSC} \qquad \textit{Equation 7}$$

$$X_{D-TCSC} = rtcsc.X_{Line} \qquad \textit{Equation 8}$$

$$-0.7 \leq rtcsc \leq 0.2 \qquad \textit{Equation 9}$$

3.1.2 Problem Formulation

The problem is formulated as an objective function with a goal of minimization. Power flow problems of power systems are nonlinear problems. In such type of problems, one has to find out the magnitude of bus voltages, bus angles, active and reactive power generated by the generators to meet the demand of load and system losses. But the solution found should respect certain constraints. Such type of constraints are voltages of generators (those cannot exceed a set limit), active and reactive power generated by different generators (those cannot be exceeded from the maximum generation values) and bus voltages (those are set within a specified limits). Different commercial and research tools are available to solve such types of nonlinear problems like PSAT, Matlab, and PSS/E. In this research, Matpower has been used for formulation of power flow equations and then Knitro [19] has been used for solving the set of these nonlinear equations. Matpower is a Matlab power flow solver that allows modifications of basic formulation easily [18]. Objective function formulated is expressed mathematically in Equation 10:

Minimize

$$C_{Total} = C_1(P_G) + C_2(Q_G) + C_3(f) \qquad \textit{Equation 10}$$

Subject to:

$$g(x) = 0$$

$$h(x) \leq 0$$

Here C_{Total} is the total cost of generation that includes the cost assigned to generation of active power (C_1), cost of reactive power generation (C_2) and the cost of D-TCSC devices (C_3) those have been installed on certain lines selected on the basis of reduction of losses. The purpose is to minimize this objective function subject to equality and inequality constraints. Equality constraints can be defined for each bus as the sum of power injected (P_{Gi}), power demand of load (P_{Di}) and losses of the lines connecting the buses to the rest of the system (P_i). Inequality generation constraints are defined for each generator as active power generation (P_{Gi}), reactive power generation (Q_{Gi}) and voltage of generator (V_{Gi}). Inequality security constraints are bus voltage (V_i) of each bus and the thermal limit of each line (S_{Li}), meaning the maximum power transfer that a line can support. So in power flow problems, the equality constraints should be equal to zero and inequality constraints should be less than the set limits.

Equality Constraints:

$$-P_{Gi} + P_i + P_{Di} = 0$$

$$-Q_{Gi} + Q_i + Q_{Di} = 0$$

Inequality Constraints:

$$P_{Gi}(\min) \leq P_{Gi} \leq P_{Gi}(max)$$

$$Q_{Gi}(min) \leq \mathrm{Q_{Gi}} \leq Q_{Gi}(max)$$

$$V_{Gi}(min) \leq V_{Gi} \leq V_{Gi}(\max)$$

$$V_i(min) \leq V_i \leq V_i(max)$$

$$S_{Li} \le S_{Li}(max)$$

In the objective function, cost associated to active power generation (C_1) and reactive power generation cost (C_2) can be shown by equations as under [12]:

$$C_1(P_G) = \alpha_2 P^2 + \alpha_1 P + \alpha_0 \;\; US\,\$/hr \qquad \textit{Equation 11}$$

$$C_2(Q_G) = \beta_1(Q) + \beta_0 \; US\;\$/hr \qquad \textit{Equation 12}$$

Whereas the cost of each D-TCSC (C_3), has been calculated by the equation below.

$$C_3(f) = C_{TCSC} \times S \times 1000 \; US\,\$ \qquad \textit{Equation 13}$$

Where C_{TCSC} has been taken from [13]

$$C_{TCSC} = 0.0015S^2 - 0.7130S + 153.75 \; US\;\$/KVar$$

Here S is the amount of reactive power flow in MVAR through that specific line. Beside the addition of the cost of Distributed Thyristor Controlled Series Capacitors installed in certain lines, to consider the effect of these installed D-TCSCs in power flow, new power flow variable X_{ij} has been introduced in formulation of power flow equations. This variable has been assigned specified lower and upper bounds those are taken from the review of the literature about the compensation level that can be provided by TCSC [17]. So these bounds are set to -0.7X_{Line} on the lower side and 0.2X_{Line} on the upper side. The new inequality constraint introduced in the power flow can be expressed as:

$$X_{Line} - 0.7X_{Line} \le X_{ij} \le X_{Line} + 0.2X_{Line}$$

From the physical structure of D-TCSC device, it can be seen that the device is consisted of a capacitor shunted by an inductor. The compensation provided by the device is a function of the firing angle of the thyristor. The equivalent reactance of a parallel LC circuit can be calculated by the equation as:

$$X_{TSR} = \frac{(jX_L)(-jX_C)}{jX_L - jX_C}$$

$$X_{TSR} = \frac{jX_C X_L}{X_C - X_L}$$

Reactance that can be provided by a D-TCSC ranges from capacitive mode (i.e $-0.7X_{Line}$) to inductive mode (i.e $0.2X_{Line}$). Considering this range of compensation, the reactance of line having D-TCSC can be defined by the mathematical relation as under:

$$0.3X_{Line} \leq X_{Line} \leq 1.2X_{Line}$$

To take the advantage of inductive mode of the device, fault current constraint has been defined taking into consideration the inductive capability of the device. Fault current constraint is a nonlinear constraint that can be defined as under

$$|I_f| = I_{Spec}$$

Where, $|I_f|$ is the magnitude of the fault current flowing from bus i to bus j when bus f is in fault and I_{Spec} is the specified fault current magnitude. The fault current through a transmission line can be calculated by the expression as under [34]

$$If = \frac{V_i - V_j - FSF \times V_f}{Z_{ij}}$$

Where V_i , V_j , V_f are the voltages of buses i , j , f respectively and Z_{ij} is the impedance of transmission line connecting bus i with bus j. FSF is a function of impedance bus elements that can be defined by mathematical relation as under:

$$FSF = \frac{Zbus_{if} - Zbus_{jf}}{Zbus_{ff}}$$

$Zbus_{if}$, $Zbus_{jf}$, $Zbus_{ff}$ are ij , jf and ff elements of impedance matrix of the power system. Keeping in view all the above mathematical expressions, two different variables labeled X_C and X_{TSR} have been created against each D-TCSC device. X_C has been considered in formulation of power flow equations those are the function of admittance matrix of the power system. So, the lower and upper bounds for X_C has been defined to keep it in the capacitive range and has been considered in bus power flow equality and branch flow inequality constraints. The range for X_C is defined by the relation as under:

$$0.3X_{Line} \leq X_C \leq X_{Line}$$

X_{TSR} has been considered in the fault current constraints that is a function of bus voltages and impedance matrix of the power system. The range for X_{TSR} has been defined such as to keep it in the inductive mode to limit the fault current through a transmission line.

$$0 \leq X_{TSR} \leq 0.2X_{Line}$$

New nonlinear fault current constraint and power flow equations with new nonlinear variable X_C are combined to make power flow problem. Objective function, *f*, is modified to consider the cost of the D-TCSC devices and cost of active power generation so that X_C and X_{TSR} are pushed to minimum possible value of compensation. Objective function is optimized with an objective to minimize it by using Knitro Optimizer tool.

From the relation under:

$$X_{TSR} = \frac{jX_C X_L}{X_C - X_L}$$

It can be seen that the value of X_L cannot be equal to X_C as the device will be in oscillation mode that means the reactance will be oscillating between capacitive and inductive modes of operation as the equation will have two roots at this condition. So, the condition emerges can be defined mathematically as under and defined in power flow problem as a linear constraint.

$$X_L \leq 0.7X_C$$

$$X_{TSR} \leq \frac{7}{3} X_C$$

3.1.3 Flow Chart of Proposed Methodology

Flow chart of the proposed methodology is shown in Figure 13. First of all, case data from the case file having information about system buses, generators, branches and available D-TCSCs will be loaded to make a Matpower case structure. If no D-TCSC is available, the conventional power flow variables (magnitude of bus voltages, bus angles, active and reactive power injected by each generator) will be created and lower and upper bounds will be assigned to these variables. Matpower case structure for IEEE 06-Bus System without D-TCSCs is shown in Figure 11.

```
mpc =
  version: '2'
  baseMVA: 100
      bus: [6x17 double]
      gen: [3x25 double]
   branch: [11x21 double]
  gencost: [3x7 double]
    order: [1x1 struct]
```

Figure 11 Matpower Case Structure without D-TCSCs

If D-TCSCs are available on certain lines, a new power flow variable against each available D-TCSC will be created and lower and upper limits will be assigned to each new variable as defined in equation above. Matpower case structure of IEEE 06-Bus system with D-TCSCs has been shown in Figure 12. If fault current constraint is defined in case data, then a new nonlinear constraint will be added as a fault current constraint. Then Objective function will be modified to consider the cost of the available D-TCSCs in the power system.

```
mpc =
       version: '2'
       baseMVA: 100
           bus: [6x17 double]
           gen: [3x25 double]
        branch: [11x21 double]
       gencost: [3x7 double]
          TCSC: [6x2 double]
    constraint: [2 3 5 100]
         order: [1x1 struct]
```

Figure 12 Matpower Case Structure with D-TCSCs and Fault Current Constraint

After that, starting points will be selected for all available power flow variables and Knitro optimizer will be executed to find out an optimal solution of this nonlinear problem. If constraints are violated for this starting point of variables, a new starting point will be selected by using multistart_enable (Ms_Enable) feature of Knitro optimizer.

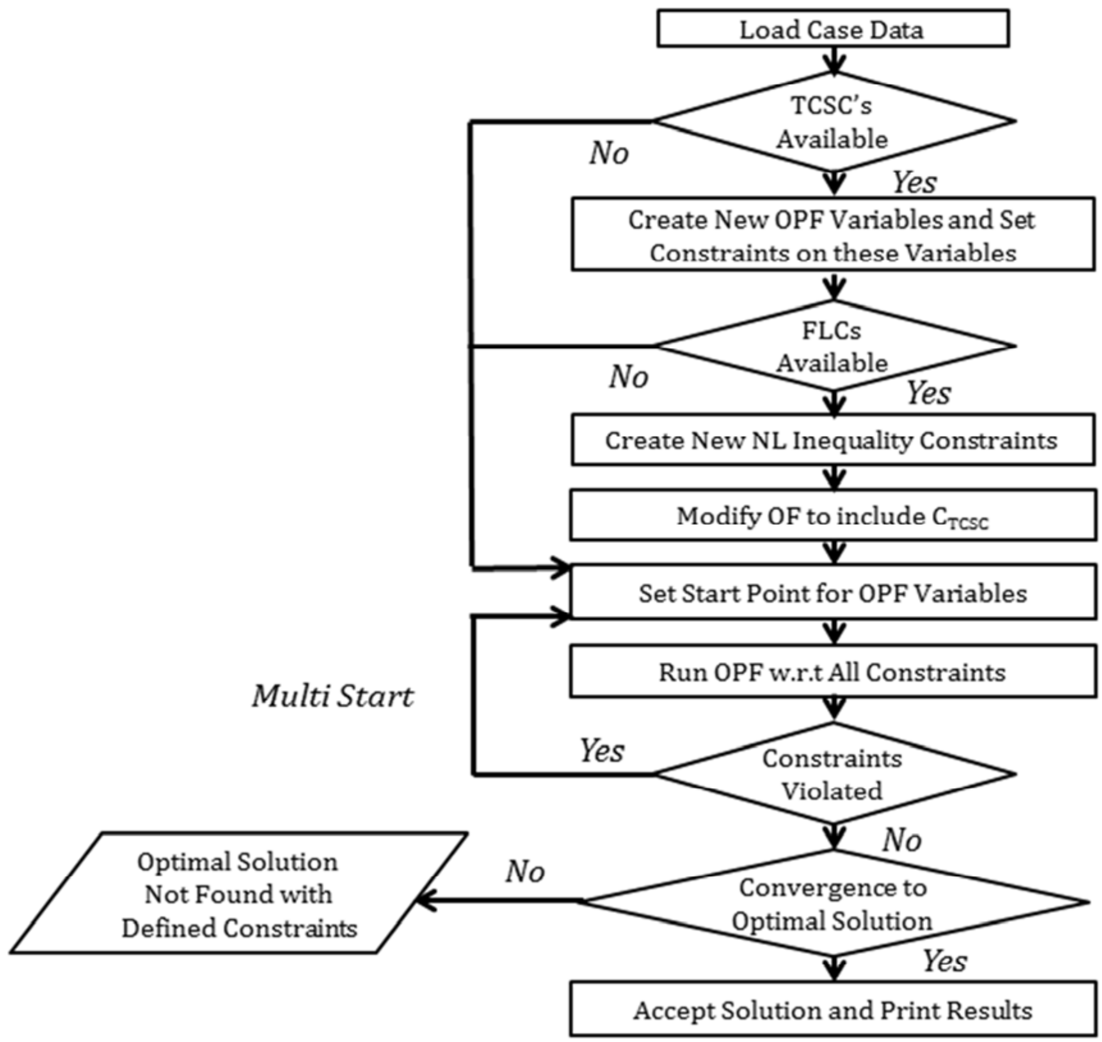


Figure 13 Flow Chart of Methodology

If constraints are not violated and an optimal solution is found, results will be displayed. Otherwise there is notified that a solution with the specified constraints is not feasible. In that case, some of the constraints could be relaxed and the problem could be reformulated so that an optimal feasible solution is found.

4 CHAPTER

4.1 OPTIMAL POWER FLOW

Proposed Methodology has been tested on 06-Bus and 30-Bus IEEE cases. AC Optimal Power Flow has been executed on both test systems by using Matpower / Knitro Optimizer. The results for both cases have been presented and analyzed in this section.

4.1.1 06-Bus Power System

06-Bus power system is shown in Figure 14. AC Optimal Power flow has been executed on this power system without adding any D-TCSC device.

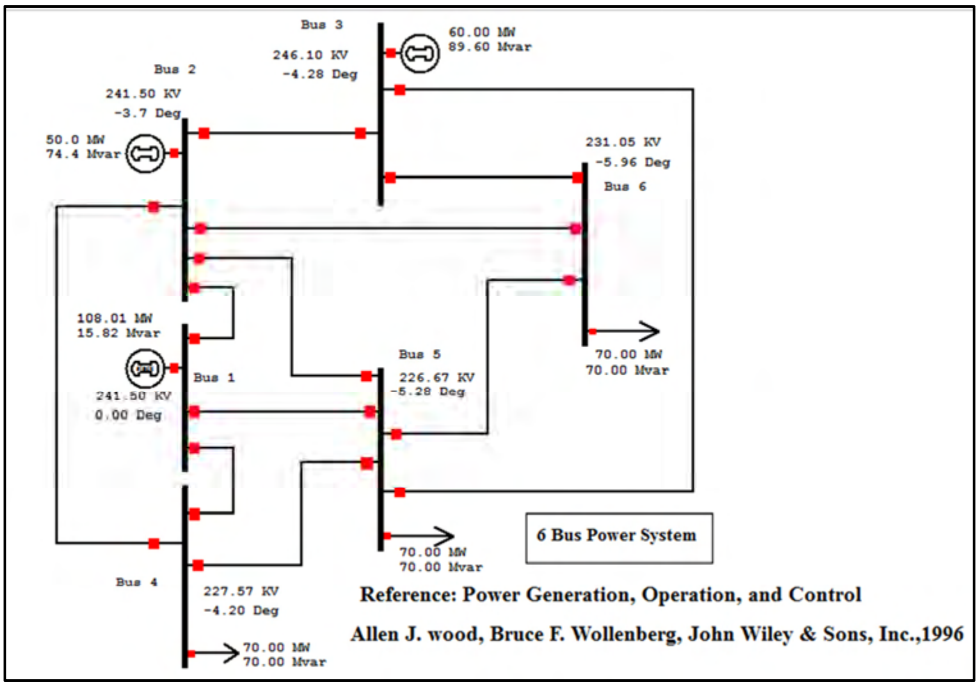
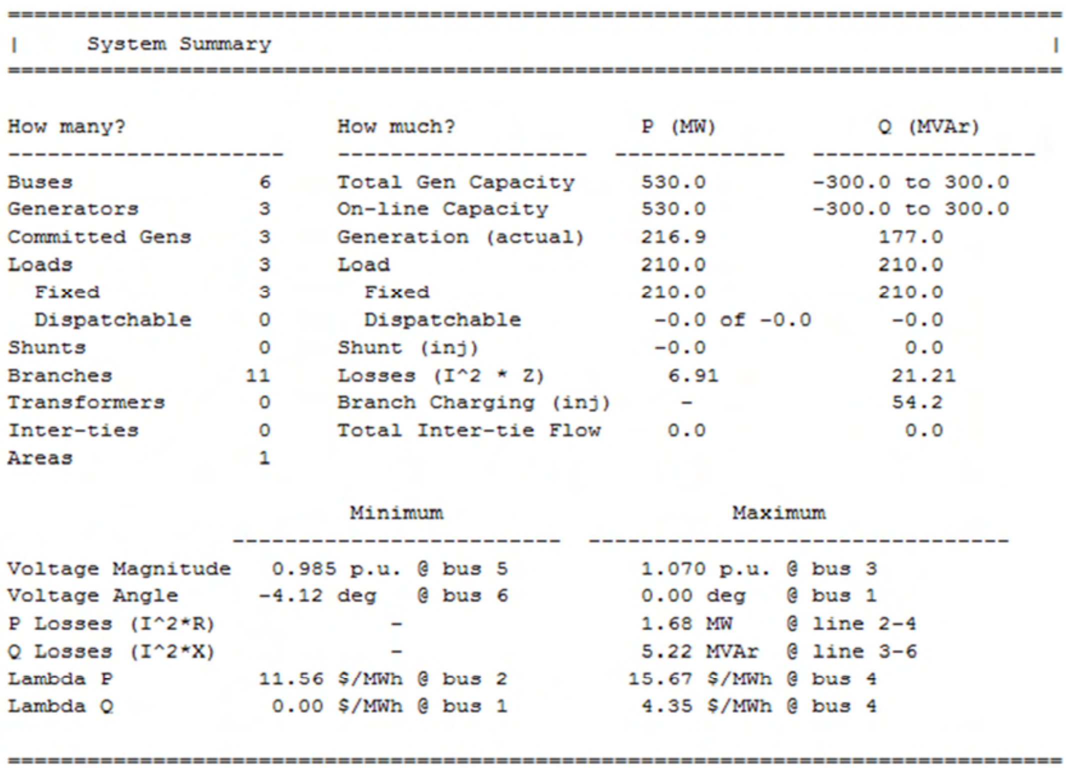


Figure 14 06-Buses Power System without D-TCSCs [20]

Matpower has a good feature of displaying comprehensive summary of power system under analysis as shown in Figure 15. In system summary under the heading of “How many?” one can see that 06-Bus Power System has six buses, three generators, eleven branches, three fixed loads while all buses are in Area 1. Under the heading “How much?” it can be seen that total generation capacity of generators is 530 MW and -300 MVAR to 300 MVAR. The active power demand of all three loads is 210 MW and reactive power demand is 210 MVAR. Active power dissipation in branches is 6.91 MW and reactive power loss in branches is 21.21 MVAR. The active power demand of loads and active power line losses are being met by the total generation of 216.9 MW from all three generators. Whereas, reactive power demand of loads and reactive power line losses are met by reactive power generation of 177 MVAR from all three generators and 54.2 MVAR of branch charging injection while shunt injection in this case is 0 MVAR.

Furthermore, it is also shown that minimum voltage magnitude is 0.985 pu at bus No. 5 and maximum voltage magnitude is 1.070 pu at bus No. 3. Line 2-4 is dissipating maximum active power that is 1.68 MW and Line 3-6 has maximum loss of 5.22 MVAR.



```
================================================================================
|     System Summary                                                           |
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses              6     Total Gen Capacity     530.0           -300.0 to 300.0
Generators         3     On-line Capacity       530.0           -300.0 to 300.0
Committed Gens     3     Generation (actual)    216.9              177.0
Loads              3     Load                   210.0              210.0
  Fixed            3       Fixed                210.0              210.0
  Dispatchable     0       Dispatchable          -0.0 of -0.0       -0.0
Shunts             0     Shunt (inj)             -0.0                0.0
Branches          11     Losses (I^2 * Z)         6.91              21.21
Transformers       0     Branch Charging (inj)     -                54.2
Inter-ties         0     Total Inter-tie Flow     0.0                0.0
Areas              1

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   0.985 p.u. @ bus 5          1.070 p.u. @ bus 3
Voltage Angle      -4.12 deg   @ bus 6          0.00 deg   @ bus 1
P Losses (I^2*R)             -                  1.68 MW    @ line 2-4
Q Losses (I^2*X)             -                  5.22 MVAr  @ line 3-6
Lambda P           11.56 $/MWh @ bus 2         15.67 $/MWh @ bus 4
Lambda Q            0.00 $/MWh @ bus 1          4.35 $/MWh @ bus 4

================================================================================
```

Figure 15 System Summary of 06-Bus Power System without D-TCSCs

After successful convergence of 06-Bus power system to an Optimal solution, in Bus Data shown in Figure 16, individual bus voltage magnitude (pu), bus voltage angle (deg), active power generation (MW) and reactive power generation (MVAR) of individual generators connected with respective bus number is displayed.

Bus #	Voltage Mag(pu)	Voltage Ang(deg)	Generation P (MW)	Generation Q (MVAr)	Load P (MW)	Load Q (MVAr)	Lambda($/MVA-hr) P	Lambda($/MVA-hr) Q
1	1.050	0.000*	77.22	25.72	-	-	12.492	-
2	1.050	-1.985	69.27	64.65	-	-	11.565	-
3	1.070	-2.237	70.42	86.64	-	-	11.877	-
4	0.988	-3.069	-	-	70.00	70.00	15.674	4.345
5	0.985	-3.920	-	-	70.00	70.00	12.939	1.169
6	1.005	-4.118	-	-	70.00	70.00	12.206	0.423
		Total:	216.91	177.01	210.00	210.00		

Figure 16 Bus Data of 06-Bus Power System without D-TCSCs

In displayed results under Branch Data heading as shown in Figure 17, from bus injection and to bus injection of active power in MW and reactive power in MVAR for each branch is shown. Moreover I^2R losses in MW and I^2X losses in MVAR are also shown against respective branches. Total of active and reactive power losses of all the branches is also calculated and shown at the end of the table. From where it can be seen that total active power loss of all the branches is 6.91 MW and sum of reactive power losses is 21.21 MVAR. These figures of total line losses have also been shown in System Summary shown in Figure 15.

Brnch #	From Bus	To Bus	From Bus Injection P (MW)	From Bus Injection Q (MVAr)	To Bus Injection P (MW)	To Bus Injection Q (MVAr)	Loss (I^2 * Z) P (MW)	Loss (I^2 * Z) Q (MVAr)
1	1	2	15.41	-9.58	-15.14	5.70	0.265	0.53
2	1	4	33.95	22.50	-33.15	-23.46	0.799	3.20
3	1	5	27.86	12.80	-27.11	-16.20	0.751	2.82
4	2	3	0.29	-11.76	-0.25	5.18	0.032	0.16
5	2	4	41.74	43.11	-40.06	-41.83	1.676	3.35
6	2	5	17.35	14.93	-16.81	-17.46	0.540	1.62
7	2	6	25.03	12.67	-24.49	-16.38	0.549	1.57
8	3	5	23.18	21.57	-21.99	-24.28	1.189	2.58
9	3	6	47.50	59.90	-46.45	-56.82	1.045	5.22
10	4	5	3.21	-4.71	-3.19	-3.03	0.022	0.04
11	5	6	-0.90	-9.03	0.94	3.21	0.039	0.12
						Total:	6.908	21.21

Figure 17 Branch Data of 06-Bus Power System without D-TCSCs

From the solution of 06-Bus system displayed above, six lines having highest value of reactive power loss are selected. In each branch, a D-TCSC is introduced. For this purpose, a vector of variable Xij of dimension 6x1 was constructed and lower and upper bounds were set as already discussed in 3.1.2. A sorted list of branches on the basis of reactive power line loss showing status of installed D-TCSCs is presented in Table 1.

Table 1 List of Branches of 06-Bus System

Branch #	From Bus	To Bus	Q Line Loss (MVAR)	D-TCSC Installed (Yes/No)
9	3	6	5.22	Yes
5	2	4	3.35	Yes
2	1	4	3.2	Yes
3	1	5	2.82	Yes
8	3	5	2.58	Yes
6	2	5	1.62	Yes
7	2	6	1.57	No
1	1	2	0.53	No
4	2	3	0.16	No
11	5	6	0.12	No
10	4	5	0.04	No

Then structure of 06-Bus power system with installed Distributed Thyristor Controlled Series Capacitor devices in six lines has been shown in Figure 18. AC optimal power flow has been re-executed and the results of the said case without D-TCSCs and with D-TCSCs have been analyzed and an improvement in voltage profile with reduced system losses of the power system has been observed.

As from the results of convergence to an optimal solution for 06-Bus system after addition of six D-TCSC devices on certain lines as shown in Table 1, it can be seen from System Summary shown in Figure 19 that active power generation is 216.7 MW and reactive power generation is reduced to 165 MVAR. Active power line losses are 6.67 MW and reactive power line losses have been reduced to 7.81 MVAR. Maximum active power dissipation is 1.6 MW across line 2-4 and highest reactive power being dissipated is 2.72 MVAR across line 3-6.

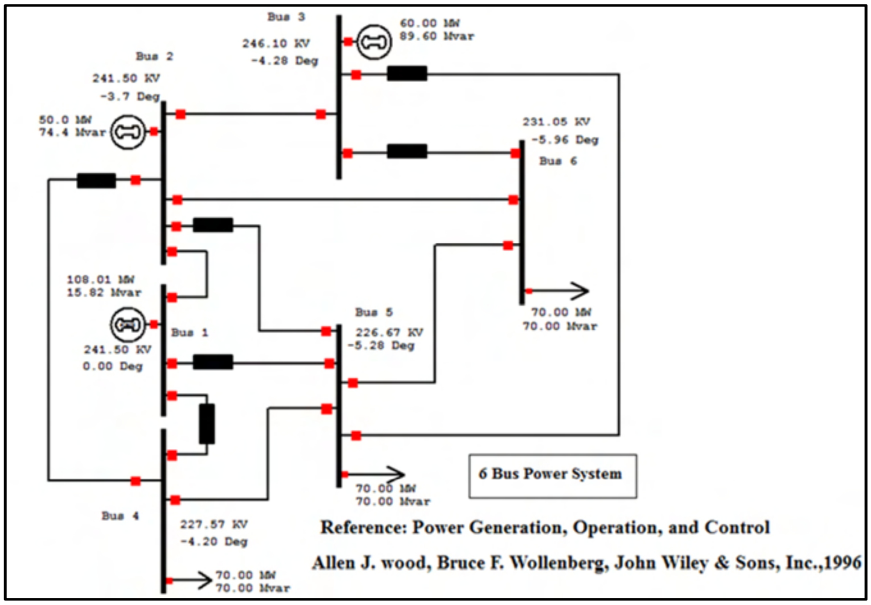


Figure 18 06-Buses Power System with D-TCSCs

```
================================================================================
|     System Summary                                                           |
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses                6   Total Gen Capacity     530.0           -300.0 to 300.0
Generators           3   On-line Capacity       530.0           -300.0 to 300.0
Committed Gens       3   Generation (actual)    216.7               165.8
Loads                3   Load                   210.0               210.0
  Fixed              3     Fixed                210.0               210.0
  Dispatchable       0     Dispatchable          -0.0 of -0.0        -0.0
Shunts               0   Shunt (inj)             -0.0                 0.0
Branches            11   Losses (I^2 * Z)         6.67                7.81
Transformers         0   Branch Charging (inj)     -                 52.0
Inter-ties           0   Total Inter-tie Flow     0.0                 0.0
Areas                1

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   0.980 p.u. @ bus 5          1.020 p.u. @ bus 2
Voltage Angle      -0.64 deg   @ bus 6          0.19 deg   @ bus 3
P Losses (I^2*R)             -                  1.60 MW    @ line 2-4
Q Losses (I^2*X)             -                  2.72 MVAr  @ line 3-6
Lambda P           10.21 $/MWh @ bus 3      68777.83 $/MWh @ bus 5
Lambda Q            1.15 $/MWh @ bus 2      192023.83 $/MWh @ bus 5

================================================================================
```

Figure 19 System Summary of 06-Bus Power System with D-TCSCs

From bus data shown in Figure 20, improvement in bus voltage magnitude can be seen.

Now bus voltage magnitude of all buses is within ±2% of desired unity voltage level. Moreover, reactive power generation has been significantly reduced from 177 MVAR to 165 MVAR due to decrease in reactive power line losses from 21.21 MVAR to 7.81 MVAR. From the branch data of solution shown in Figure 21, active and reactive power line losses can be seen against each line and it is observed that active power line losses are almost same whereas significant reduction in reactive power line losses has been noted.

Bus Data

Bus	Voltage		Generation		Load		Lambda ($/MVA-hr)	
#	Mag(pu)	Ang(deg)	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)	P	Q
1	1.020	0.000*	50.04	50.97	-	-	4043.934	1.403
2	1.020	-0.001	80.33	54.44	-	-	11.885	1.154
3	1.020	0.187	86.29	60.36	-	-	10.211	2.314
4	0.987	0.089	-	-	70.00	70.00	12217.760	118703.999
5	0.980	-0.142	-	-	70.00	70.00	68777.834	192023.828
6	0.985	-0.640	-	-	70.00	70.00	31275.840	107586.175
		Total:	216.67	165.77	210.00	210.00		

Figure 20 Bus Data of 06-Bus Power System with D-TCSCs

Branch Data

Brnch	From	To	From Bus Injection		To Bus Injection		Loss (I^2 * Z)	
#	Bus	Bus	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)	P (MW)	Q (MVAr)
1	1	2	0.00	-2.08	-0.00	-2.08	0.000	0.00
2	1	4	25.98	32.21	-25.09	-35.17	0.890	1.07
3	1	5	24.05	20.84	-23.16	-25.85	0.886	1.00
4	2	3	-1.31	-2.86	1.31	-3.38	0.001	0.00
5	2	4	47.98	30.88	-46.39	-31.94	1.596	0.96
6	2	5	23.11	16.95	-22.25	-20.15	0.861	0.80
7	2	6	10.56	11.55	-10.35	-15.98	0.210	0.60
8	3	5	26.10	9.58	-25.14	-13.96	0.957	0.62
9	3	6	58.87	54.19	-57.62	-53.48	1.253	2.72
10	4	5	1.48	-2.88	-1.47	-4.84	0.007	0.01
11	5	6	2.02	-5.20	-2.01	-0.56	0.010	0.03
						Total:	6.670	7.81

Figure 21 Branch Data of 06-Bus Power System with D-TCSCs

4.1.1.1 Voltage Magnitude (pu)

From Table 2, it can be seen that there is a decrease in pu voltage magnitudes of 5% at bus no. 3, decrease of 3% at bus no. 1 & 2 and decrease of 2% at bus no. 6 as compared to pu voltage magnitude of these buses without any D-TCSCs. PU voltage magnitudes of bus no. 4 & 5 are almost same in both cases.

Table 2 Bus Voltage Magnitude (pu) of 06-Bus System

Bus #	Voltage Magnitude (pu) Without D-TCSCs	Voltage Magnitude (pu) With D-TCSCs
1	1.05	1.020
2	1.05	1.020
3	1.07	1.020
4	0.988	0.987
5	0.985	0.980
6	1.005	0.985

Contour of pu voltage magnitude of buses for 06-Bus power system without D-TCSCs and with D-TCSCs has been plotted in Figure 22 and Figure 23 on a scale of 0.93 to 1.07 that is ±7% of the desired pu voltage magnitude of unity.

Without D-TCSCs, pu voltage magnitude of bus 3 is 7% above unity, buses 1 & 2 is 5% above unity, bus 6 is unity, bus 4 is 1.2% below unity and bus 5 is 1.5% below unity. So overall variation in pu voltage magnitude of all buses is +7% to -1.5% of unity voltage magnitude whereas average pu voltage magnitude of power system is 1.02 pu as shown in Figure 22.

After addition of D-TCSC devices in the power system, it is noticed that pu voltage magnitude of bus 3 is 2% above unity, buses 1 & 2 is 2% above unity, bus 6 is 1.5% below unity, bus 4 is 1.3% below unity and bus 5 is 2% below unity. Overall variation in pu voltage magnitude of power system is now in the range of ±2% and average voltage magnitude has been improved to the desired value of unity as shown in Figure 23.

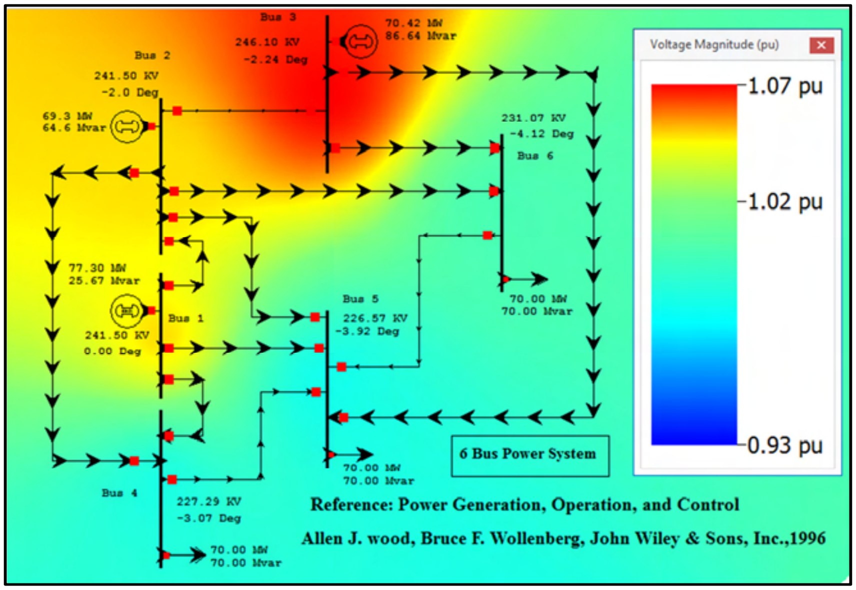


Figure 22 Voltage Magnitude (pu) without D-TCSCs

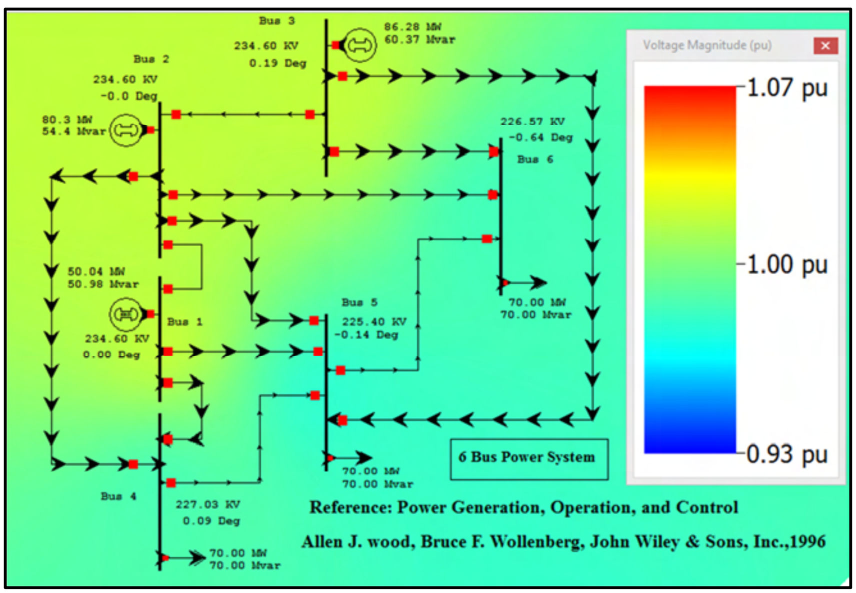


Figure 23 Voltage Magnitude (pu) with D-TCSCs

4.1.1.2 MVAR Line Losses

Contours for MVAR line losses of the 06-Bus power system without D-TCSCs and with D-TCSCs have been plotted on the scale of 0-5 MVAR as shown in Figure 24 and Figure 25. Without D-TCSCs total MVAR line losses of the system are 21.21 MVAR as shown in Figure 17 where lines 3-6, 2-4 and 1-4 are dissipating highest reactive power of

5.22 MVAR, 3.35 MVAR and 3.2 MVAR respectively. Average MVAR line losses of the system without D-TCSCs as shown in Figure 24 are 2 MVAR.

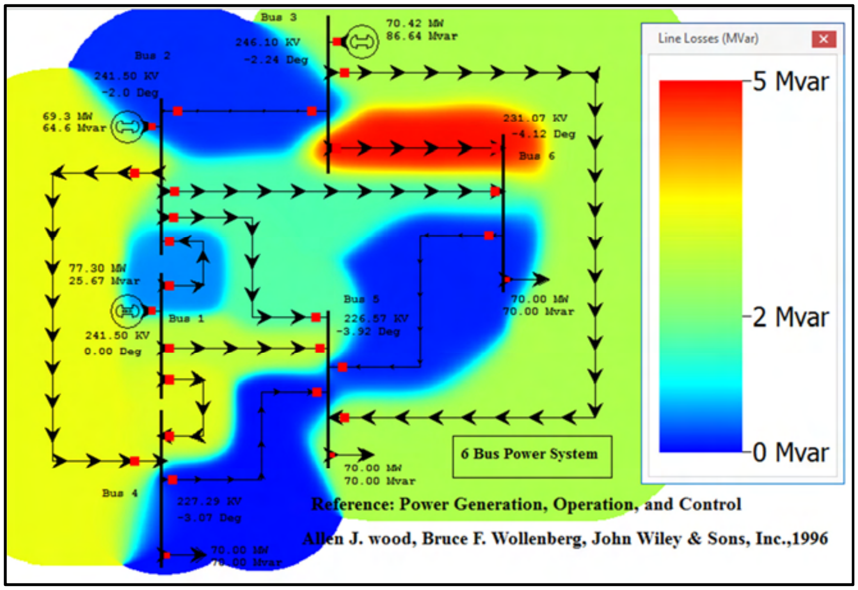


Figure 24 MVAR Line Losses without D-TCSCs

With addition of D-TCSC devices, a significant drop in MVAR line losses can be observed in the power system.

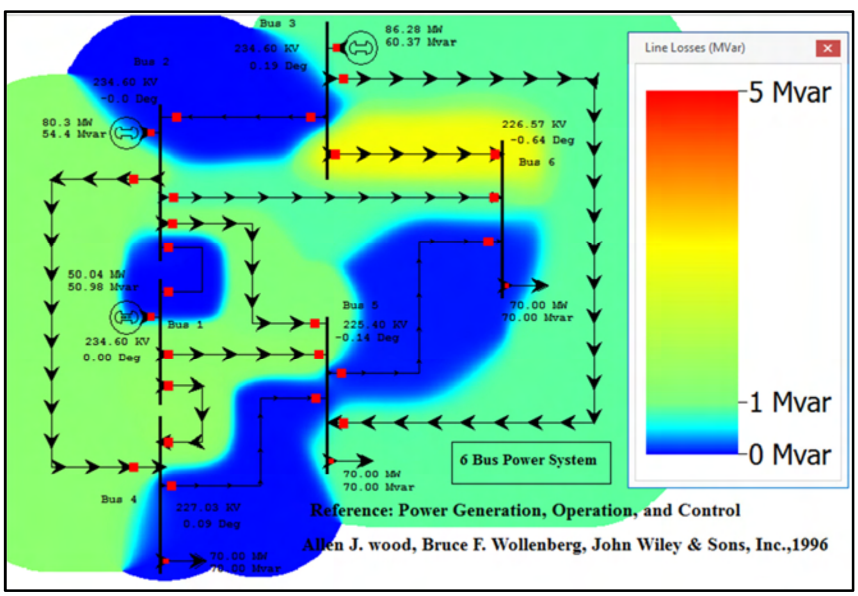


Figure 25 MVAR Line Losses with D-TCSCs

It can be observed form the contour of MVAR line losses shown in Figure 25 that MVAR line losses of lines 2-4, 3-5 and 3-6 are noticeably reduced. Small decrease in MVAR losses of lines 1-2 and 1-4 is observed whereas lines 1-5, 2-3, 2-6, 4-5 and 5-6 dissipating almost same amount of reactive power. At the same time an increase in reactive power dissipation across line 2-5 due to an increase in flow of power. Average reactive power loss of lines in the power system with addition of D-TCSCs is significantly reduced from 2 MVAR to 1 MVAR as shown in Figure 24 and Figure 25.

4.1.1.3 MW Line Losses

Contours for active power dissipation in lines of 06-bus power system are plotted on a scale of 0-1.68 MW as shown in Figure 26 and Figure 27. Active power dissipation in lines 1-2, 2-6 and 3-5 is reduced. Lines 1-4, 1-5, 2-3, 4-5 and 5-6 are dissipating same amount of active power. Despite of an increase in active power dissipation noticed across lines 2-4, 2-5 and 3-6 the average active power dissipations of the power system before and after addition of D-TCSCs are almost same as shown in Figure 26 and Figure 27.

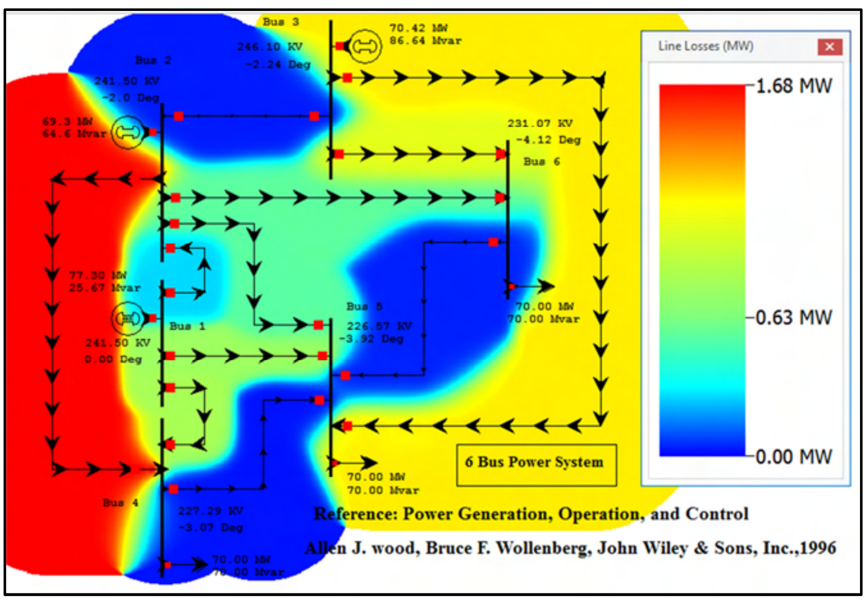


Figure 26 MW Line Losses without D-TCSCs

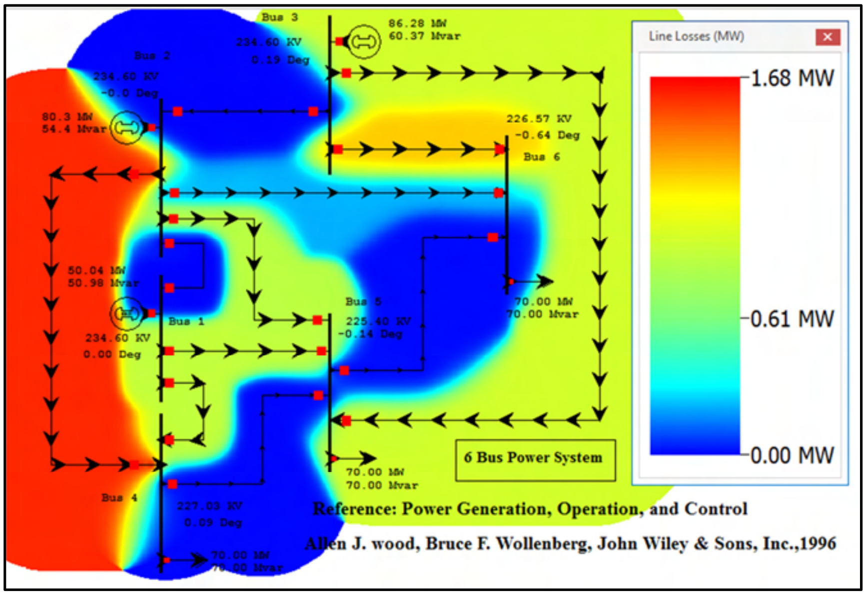


Figure 27 MW Line Losses with D-TCSCs

4.1.1.4 Lines MVAR (max)

Maximum reactive power carried by lines of power system is plotted on a scale of 0-60 MVAR. Without any D-TCSC, lines 3-6 and 2-4 are carrying highest reactive power as compared to other lines of the system. Change in reactive power flow without D-TCSCs and with D-TCSSs can be noticed in the contours shown in Figure 28 and Figure 29.

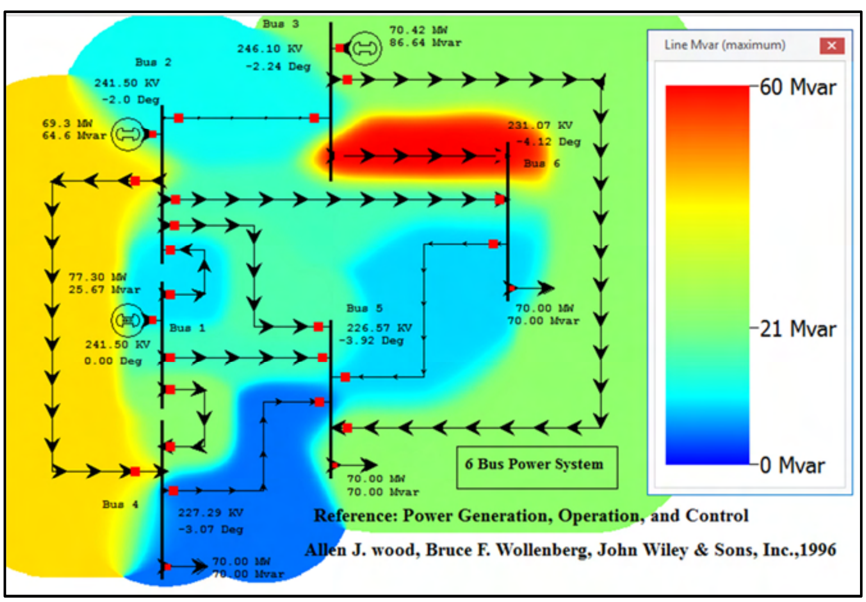


Figure 28 Lines MVAR (max) without D-TCSCs

Significant reduction in reactive power carried by lines 1-2, 2-4, 3-5 and 3-6 after the addition of D-TCSC devices has been noticed in the power system. Minute reduction in maximum reactive power carried by lines 2-3 and 5-6 is visible. Lines 2-6 and 4-5 are carrying almost same amount of reactive power. An increase in maximum reactive power carried by lines 1-4, 1-5 and 2-5 is noticed. But the average of maximum reactive power carried by lines of the system has been reduced from 21 MVAR to 19 MVAR after addition of D-TCSCs as shown in Figure 28and Figure 29.

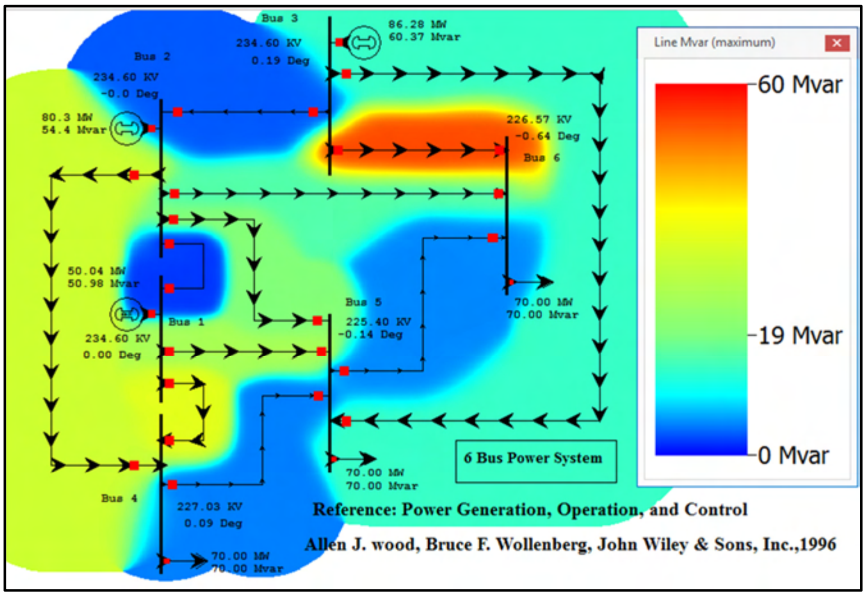


Figure 29 Lines MVAR (max) with D-TCSCs

4.1.1.5 Lines MW (max)

Maximum active power carried by lines of the power system followed same pattern as that of active power losses across lines in the system that is logical and makes sense. Contours for maximum active power carried by different lines of system are plotted on a scale of 0-60 MW as shown in Figure 30 and Figure 31. Reduction in maximum active power carried by lines 1-2, 2-6, 3-5 and same amount of maximum active power is carried by lines 1-4, 1-5, 2-3, 4-5 and 5-6. An increase observed in maximum active power carried by lines 2-4, 2-5 and 3-6. Slight decrease noticed in average value of maximum active power carried by lines after addition of D-TCSCs as shown by Figure 30 and Figure 31.

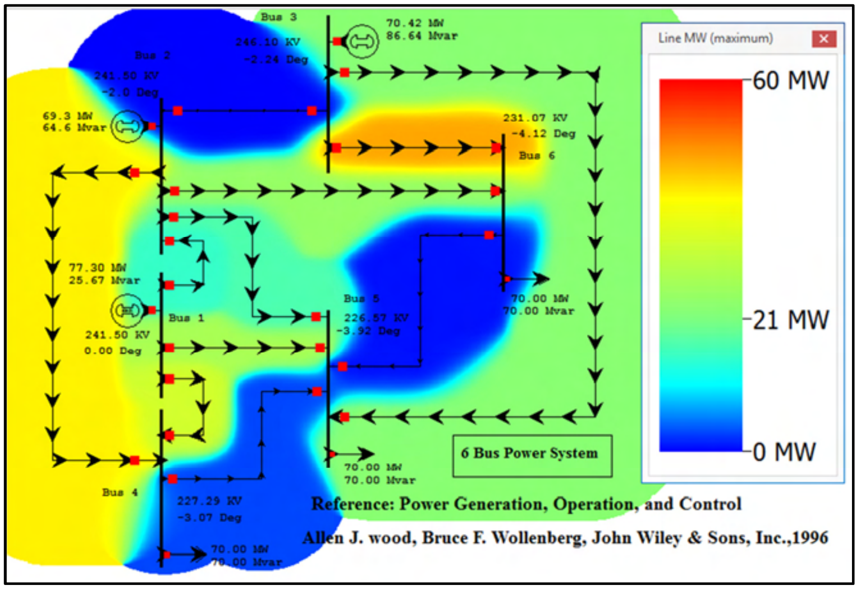


Figure 30 Lines MW (max) without D-TCSCs

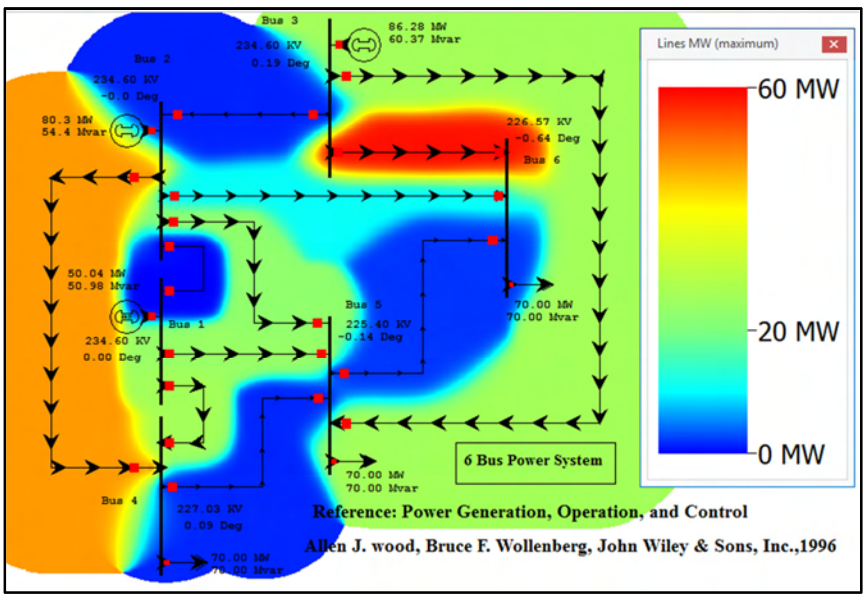


Figure 31 Lines MW (max) with D-TCSCs

4.1.1.6 Lines MVA (max)

Maximum MVA of lines in power system is shown by contours on a scale of 2-81 MVA in Figure 32 and Figure 33. Maximum apparent power carried by lines 1-2, 2-3, 2-6 is significantly reduced and maximum apparent power carried by lines 1-4, 1-5, 2-4, 3-5, 4-5, 5-6 is almost same. An increase in apparent power carried by lines 2-5 and 3-6 after addition of D-TCSCs has been observed. The average value of maximum apparent power carried by lines of the power system is decreased from 31 MVA to 28 MVA as shown in Figure 32 and Figure 33.

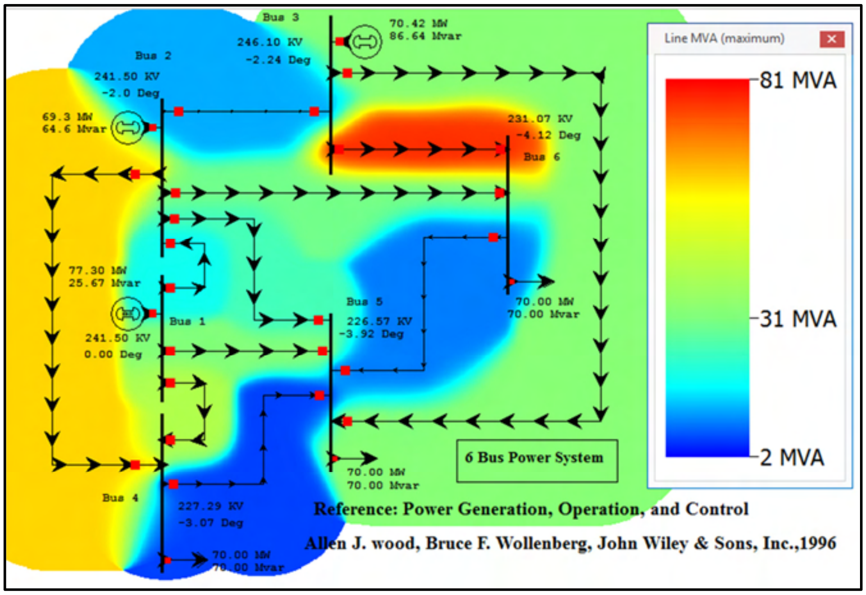


Figure 32 Lines MVA (max) without D-TCSCs

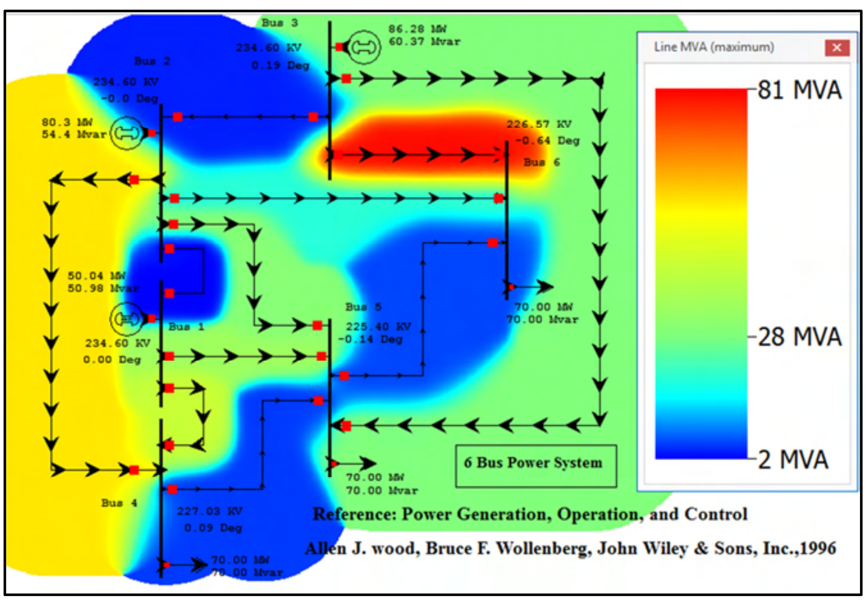


Figure 33 Lines MVA (max) with D-TCSCs

4.1.1.7 MVA Line Limit Used

For 06-bus power system, maximum line limit for flow of apparent power is 100 MVA. Contour for percentage utilization of line limit is plotted on a percentile scale of 0-80 as shown in Figure 34 and Figure 35.

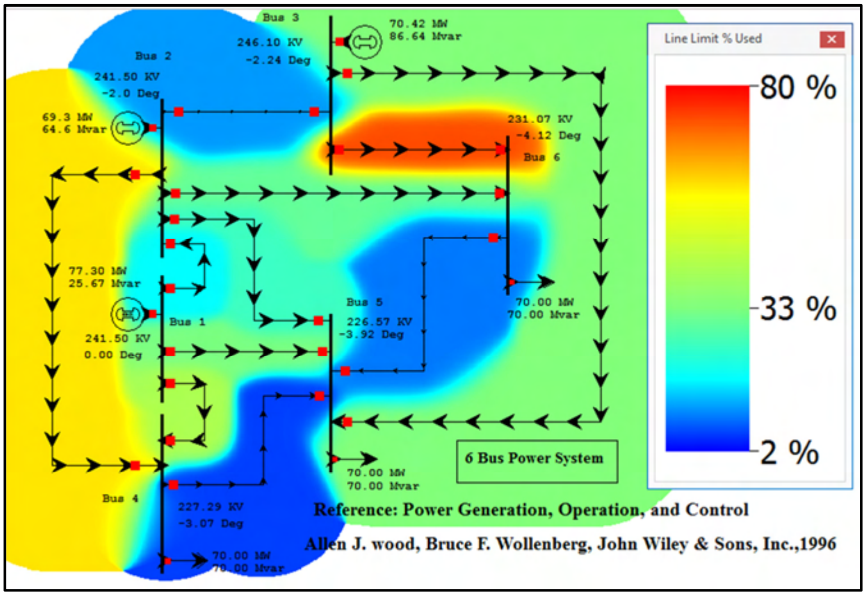


Figure 34 MVA Line Limit Used without D-TCSCs

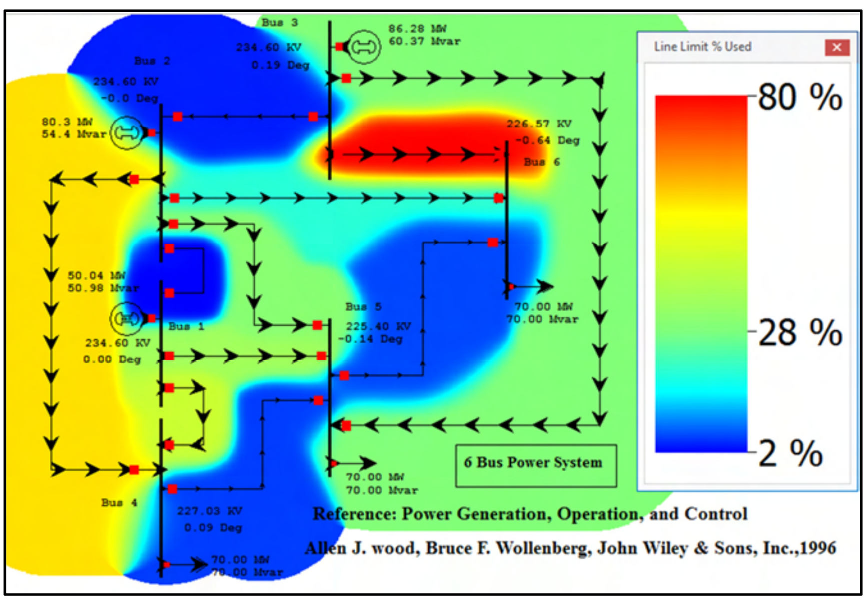


Figure 35 MVA Line Limit Used with D-TCSCs

MVA line limit used is on the same pattern as of maximum apparent power of lines. Limit of lines utilized by lines 1-2, 2-3, 2-6 is significantly reduced whereas used limit of lines 1-4, 1-5, 2-4, 3-5, 4-5, 5-6 is almost same. An increase in use of limit for lines 2-5 and 3-6 after addition of TCSC's has been observed. However the average utilization of line limits for the power system is reduced from 33% to 28% as shown in Figure 34 and Figure 35.

4.1.1.8 Generators MVA Output

The apparent power generated by each generator is plotted on a scale of 71-112 MVA as shown in Figure 36 and Figure 37. There are three generators in 06-bus power system numbered as 1, 2 and 3. These generators are connected to bus number 1, 2 and 3 respectively. Without D-TCSC devices, it can be seen from the contour of Figure 36 that generator 3 is generating maximum power , generator 2 is generating power that is close to average value of 96 MVA and generator 1 is generating apparent power slightly lower than that of average apparent power of generators output. Total apparent power generated by all the three generators can be calculated as 96X3 = 288 MVA.

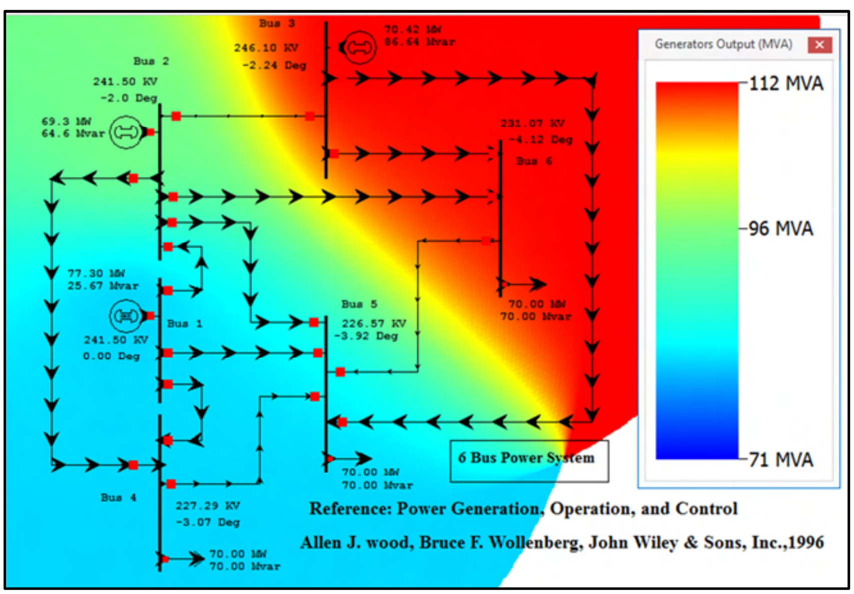


Figure 36 Generators MVA Output without D-TCSCs

With the addition of D-TCSC devices, the average apparent power of generators is reduced from 96 MVA to 91 MVA. Hence total power generated by all three generators in this case is 91X3 = 271 MVA. So an overall reduction of 17 MVA has been observed in the power system. With this significant decrease of overall generation, the decrease in power generation of individual generator is quite prominent in contour shown in Figure 37. In this contour, it is noticed that now generator 1 is generating significantly low amount of power as compared to its previous generation value that was close to 112 MVA. Generator 2 is producing power that is close to average value in this case that is 91 MVA and is significantly lower from previous average value of 96 MVA. Generator 1 is generating close to 71 MVA of power that is reduced significantly from previous case where the same generator was producing an amount of power close to 80 MV.

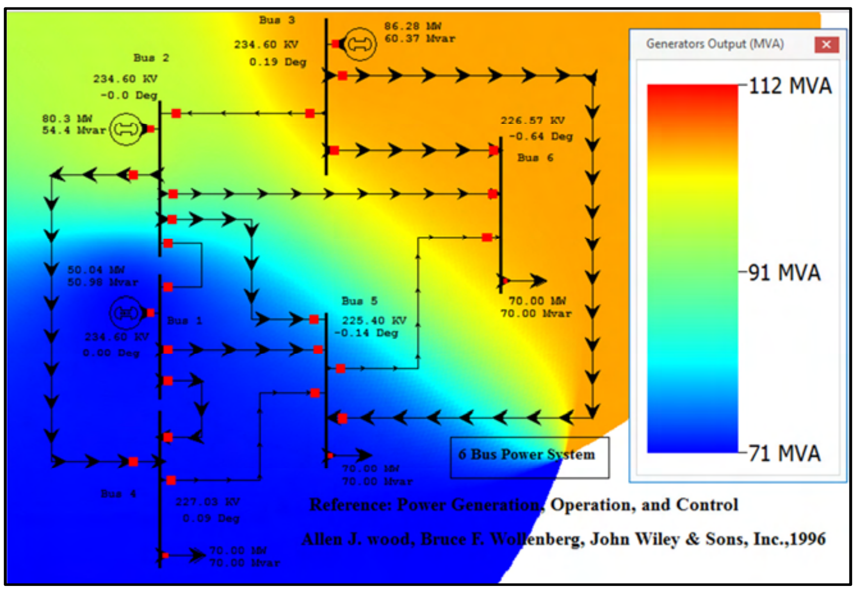


Figure 37 Generators MVA Output with D-TCSCs

4.1.1.9 Generators MVAR Output

Contours for reactive power generation of each generator without D-TCSCs and with D-TCSCs are shown in Figure 38 and Figure 39. Without adding D-TCSCs, it can be seen that generator 3 is contributing maximum reactive power that is on highest value of 87 MVAR. Generator 2 is generating 65 MVAR that is almost close to the average reactive power of 59 MVAR. Generator 1 is contributing least to the demand of reactive power by generating 26 MVAR of power. The reactive power contributed by each generator is non-uniformly distributed even when each generator has the same rating of reactive power that is -100 MVAR to 100 MVAR. There is significant difference in the values of generated power by each generator. The total reactive power demand of load that is 210 MVAR is being met by the generation of 177 MVAR.

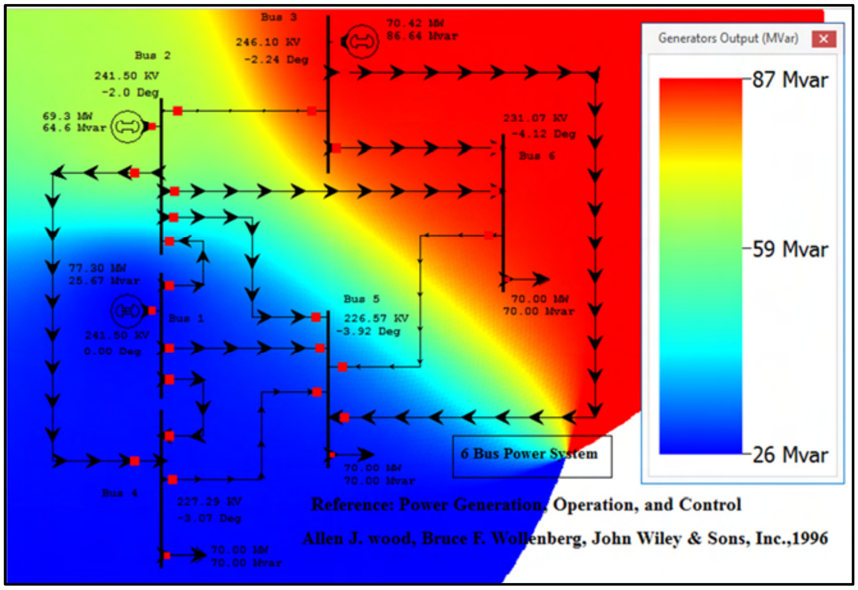


Figure 38 Generators MVAR Output without D-TCSCs

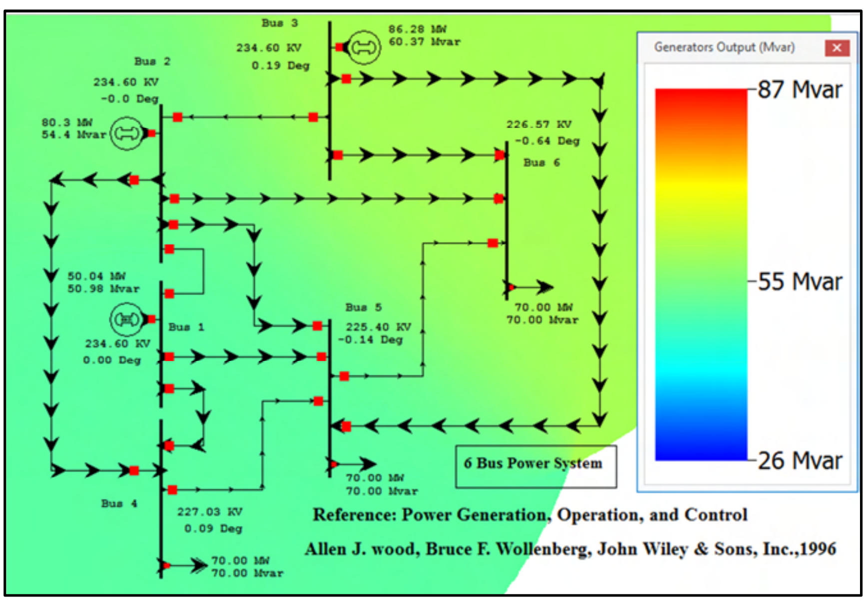


Figure 39 Generators MVAR Output with D-TCSCs

With the addition of D-TCSCs, it can be noticed from Figure 39 that average reactive power generated per generator is reduced from 59 MVAR to 55 MVAR. This reduction in average value shows that now the same reactive power demand of load is being met by generating 165 MVAR that is significantly low as compared to previous generation of 177 MVAR. Moreover from the contour shown in Figure 39, it can be seen that the contribution of each generator to the total generation of reactive power is almost same as generator 1, 2 and 3 are generating 50 MVAR, 54 MVAR and 60 MVAR respectively. These values are close to the average value of reactive power generation for the system.

4.1.1.10 Generators MW Output

Active power generation of generators has been plotted in Figure 40 and Figure 41 on a scale of 50-87 MW. From the contour shown in Figure 40, it can be seen that generator 1, 2 and 3 are generating 77 MW, 69 MW and 70 MW respectively. This amount of power generation by each generator is proportional to the maximum power generation capacity of each generator as generator 1, 2 and 3 having a maximum generation capacity of 200 MW, 150 MW and 180 MW respectively. Average generation of active power is 72 MW that means the total load demand of 210 MW is being met by the total generation of 72 X 3 = 216 MW. Amount of power generated by each generator is close to average value of generation that is 72 MW.

With the addition of D-TCSC devices in the system, it can be seen from the contour of power generation shown in Figure 41 that average value of generation is 72 MW that is exactly same as the previous one. It means the total demand of load that is 210 MW is being met by the same amount of generation of 216 MW. It makes sense as already been discussed that with the addition of D-TCSCs there is no significant change on the active power dissipation across lines as the sum of active power line losses before and after addition of D-TCSCs are same and so is the average values of active power line losses. Only the change in contribution to the total generation by each generation is noticed as previously all the three generators were generating active power close to the average value of generation. But now after addition of devices, generator 1, 2 and 3 are generating 50 MW, 80 MW and 86 MW respectively. It shows that generator 3 is now contributing maximum towards the total generated power while generator 1 is contributing least to the total generation and generator 2 is generating 80 MW that is close to average value of generation for the system. All three generators are having different cost function for active power generation and according to that generator 3 are having highest cost but even then cost of generation is almost same in both cases.

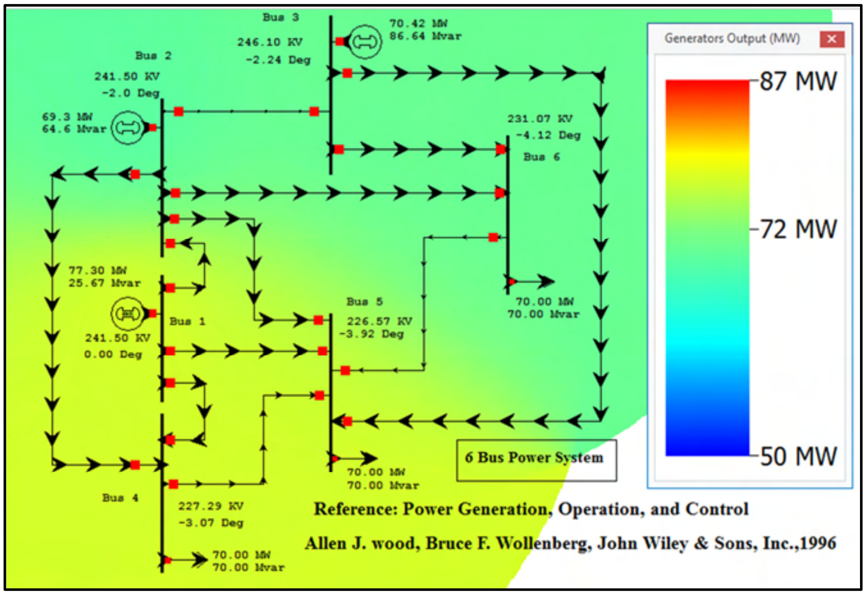


Figure 40 Generators MW Output without D-TCSCs

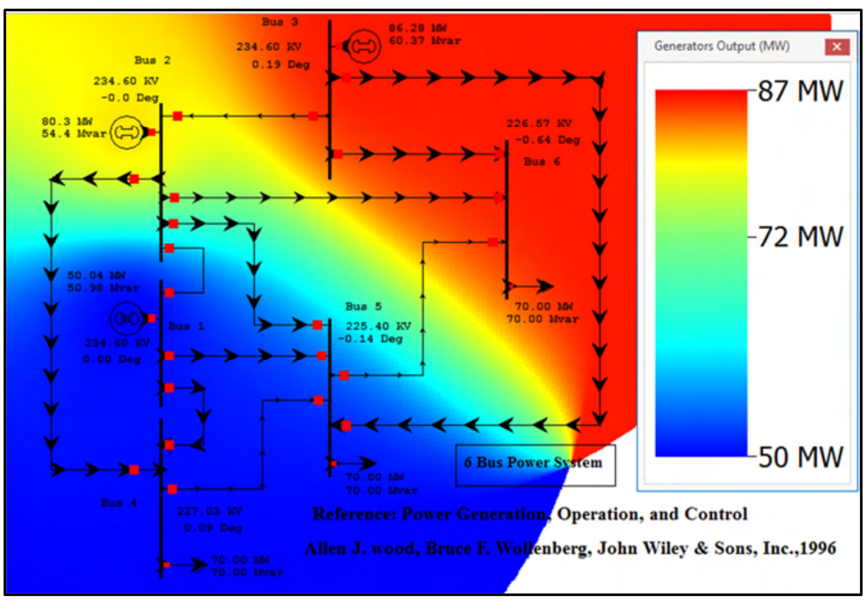


Figure 41 Generators MW Output with D-TCSCs

4.1.2 30-Bus Power System

The same methodology has been tested and verified on 30-Bus case system [21] as this is the case used by most researchers in their research work as this case is more versatile.

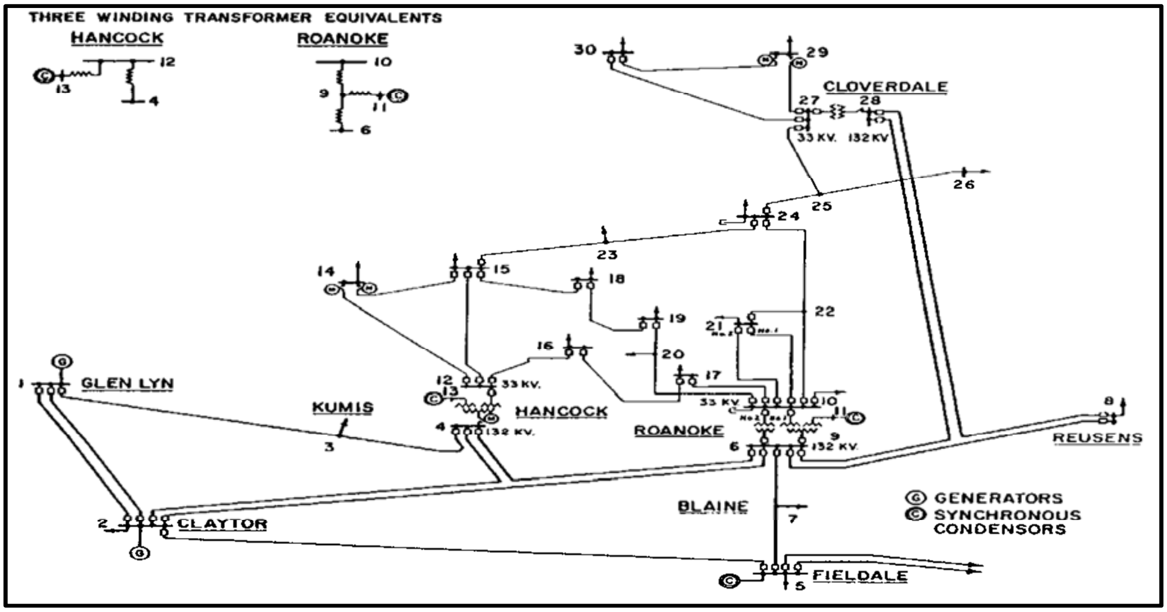


Figure 42 IEEE 30-Bus Power System [21]

Firstly the optimal power flow using Matpower and Knitro optimizer executed for the said case without adding any D-TCSC. From the results displayed after successful convergence to a local optimal solution, the system summary is shown in Figure 43. Under the heading “How many?” it can be seen that the system is having 30 buses, 6 available generators (all of them are online), 20 fixed loads, 2 shunt injections and 41 branches. The system is consisting of three different areas.

Under the heading “How much?” one can see total generation capacity of generators that is 335 MW and -95 MVAR to 405.9 MVAR with all the capacity available online as all generators are online Actual generation of all generators is 192.1 MW and 105.1 MVAR that is required to meet the total load demand of 189.2 MW and 107.2 MVAR. Shunt injection is 0.2 MVAR and branch charging injection is 15.2 MVAR. The active power dissipation across lines is 2.86 MW and reactive line loss is 13.33 MVAR. Furthermore, it is also summarized that minimum bus voltage magnitude is 0.961 pu at bus 8, maximum voltage magnitude is 1.069 pu at bus 27, minimum voltage angle -5.69 deg at bus 19, maximum voltage angle 0 deg at bus 1. Line 2-6 is dissipating maximum active power of 0.30 MW and line 28-27 is dissipating maximum reactive power of 2.39 MVAR.

```
================================================================================
|     System Summary                                                           |
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses              30    Total Gen Capacity     335.0           -95.0 to 405.9
Generators          6    On-line Capacity       335.0           -95.0 to 405.9
Committed Gens      6    Generation (actual)    192.1              105.1
Loads              20    Load                   189.2              107.2
  Fixed            20      Fixed                189.2              107.2
  Dispatchable      0      Dispatchable          -0.0 of -0.0       -0.0
Shunts              2    Shunt (inj)            -0.0                0.2
Branches           41    Losses (I^2 * Z)         2.86              13.33
Transformers        0    Branch Charging (inj)     -                15.2
Inter-ties          7    Total Inter-tie Flow    51.0               58.1
Areas               3

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   0.961 p.u. @ bus 8          1.069 p.u. @ bus 27
Voltage Angle      -5.69 deg   @ bus 19         0.00 deg   @ bus 1
P Losses (I^2*R)             -                  0.30 MW    @ line 2-6
Q Losses (I^2*X)             -                  2.39 MVAr  @ line 28-27
Lambda P            3.66 $/MWh @ bus 1          5.38 $/MWh @ bus 8
Lambda Q           -0.06 $/MWh @ bus 29         1.41 $/MWh @ bus 8

================================================================================
```

Figure 43 System Summary of 30-Bus Power System without D-TCSCs

Table 3 List of Branches of 30-Bus System with Installed D-TCSCs

Branch #	From Bus	To Bus	Q Line Loss (MVAR)	D-TCSC Installed (Yes/No)
36	28	27	2.39	Yes
16	12	13	1.92	Yes
15	4	12	0.97	Yes
6	2	6	0.90	Yes
2	1	3	0.84	Yes
3	2	4	0.66	Yes
35	25	27	0.47	Yes
10	6	8	0.43	Yes
5	2	5	0.43	Yes
33	24	25	0.41	Yes

After adding D-TCSC devices in the lines shown in Figure 44 and Table 3 (causing highest Q losses), optimal power flow re-executed and results are examined and analyzed in sections as under.

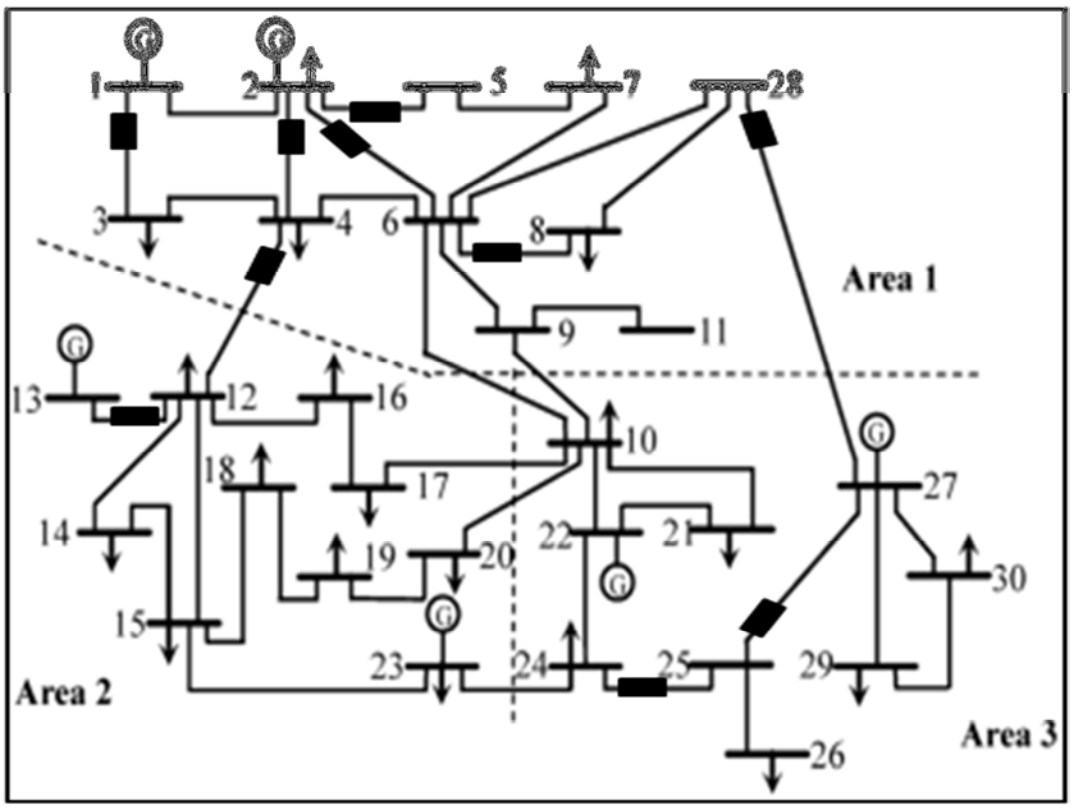


Figure 44 30-Bus Power System with D-TCSCs

From System Summary shown in Figure 45, it can be seen that the active power generation is 192 MW that is same as previous but reactive power generation in this case has been reduced to 101 MVAR. Reactive power demand of load is being met by reactive power generation of 101 MVAR, shunt injection of 0.2 MVAR and branch charging injection of 15.8 MVAR. Active power dissipation across lines is 2.74 MW (remained same) but reactive power dissipation across line has been reduced from 13.33 MVAR to 9.62 MVAR. Maximum active power dissipation is 0.22 MW across line 2-6 that is less compared to maximum power dissipation of 0.30 MW across the same line. Highest reactive power dissipation is slightly increased that is 2.57 MVAR across line 12-13, compared to 2.39 MVAR dissipation across line 28-27 but overall dissipation of reactive power across all lines has been reduced.

```
================================================================================
|     System Summary                                                           |
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses              30    Total Gen Capacity     335.0          -95.0 to 405.9
Generators          6    On-line Capacity       335.0          -95.0 to 405.9
Committed Gens      6    Generation (actual)    191.9              100.8
Loads              20    Load                   189.2              107.2
  Fixed            20      Fixed                189.2              107.2
  Dispatchable      0      Dispatchable          -0.0 of -0.0       -0.0
Shunts              2    Shunt (inj)             -0.0                0.2
Branches           41    Losses (I^2 * Z)         2.74               9.62
Transformers        0    Branch Charging (inj)     -                15.8
Inter-ties          7    Total Inter-tie Flow    59.2               44.6
Areas               3

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   0.980 p.u. @ bus 7          1.020 p.u. @ bus 22
Voltage Angle   -1079.46 deg   @ bus 25       720.87 deg   @ bus 23
P Losses (I^2*R)             -                  0.22 MW    @ line 2-6
Q Losses (I^2*X)             -                  2.57 MVAr  @ line 12-13
Lambda P        -1345.57 $/MWh @ bus 25     44733.71 $/MWh @ bus 8
Lambda Q        -2078.57 $/MWh @ bus 1     311892.65 $/MWh @ bus 8

================================================================================
```

Figure 45 System Summary of 30-Bus Power System with D-TCSCs

4.1.2.1 Voltage Magnitude (pu)

Voltage magnitude pu of all buses in the power system has been shown without D-TCSCs and with D-TCSCs in Table 4. PU voltage magnitude of all buses without D-TCSCs and with D-TCSCs has also been plotted along with desired unity voltage level in Figure 46. Without D-TCSCs, it can be seen that bus 27 is at maximum voltage of 1.07 and bus 8 is on minimum voltage level of 0.96 pu. Bus 13 and 29 are also having voltage magnitude of 1.06 and 1.05 respectively that is more than 5% above than the desired unity voltage level.

After addition of D-TCSCs in certain lines shown in Table 3, it can be noticed that bus 27 is now having pu voltage magnitude of 1.02 and buses 13 & 29 are having voltage level close to unity. The improvement in voltage level of buses after addition of D-TCSCs is quite prominent as it can be seen that voltage level of all 30 buses is now in the range of ±2% as the highest level of bus voltage is 1.02 pu and lowest voltage level is 0.98 pu. So an improvement of 2% in bus voltage levels below unity as it is brought up from 0.96 pu to 0.98 pu and an improvement of 5% in bus voltage levels above unity as these are brought down from 1.07 pu to 1.02 pu.

Table 4 Voltage Magnitude (pu) of 30-Bus Power System without and with D-TCSCs

Bus #	Voltage Mag. (pu) Without D-TCSCs	Voltage Mag. (pu) With D-TCSCs	Bus #	Voltage Mag. (pu) Without D-TCSCs	Voltage Mag. (pu) With D-TCSCs
1	0.982	0.992	16	1.003	0.988
2	0.979	1.001	17	0.995	0.993
3	0.977	0.99	18	0.993	0.982
4	0.976	0.99	19	0.987	0.98
5	0.971	0.992	20	0.99	0.985
6	0.972	0.987	21	1.009	1.013
7	0.962	0.98	22	1.016	1.02
8	0.961	0.98	23	1.026	1.02
9	0.99	0.997	24	1.017	1.01
10	1	1.003	25	1.044	1.01
11	0.99	0.997	26	1.027	0.992
12	1.017	0.991	27	1.069	1.02
13	1.065	0.993	28	0.982	0.998
14	1.007	0.985	29	1.05	1
15	1.009	0.991	30	1.039	0.989

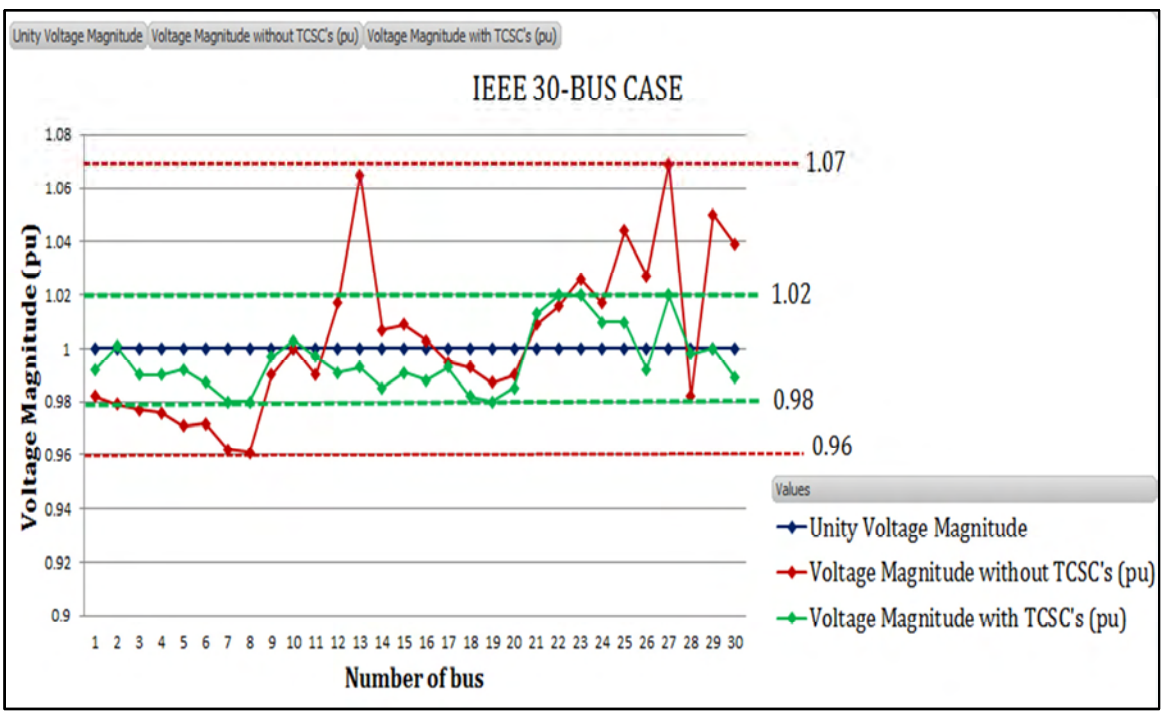


Figure 46 Voltage Magnitude (pu) without D-TCSC, with D-TCSC and Unity Voltage

4.1.2.2 MVAR Line Losses

Line losses of all branches of 30-Bus power system without D-TCSCs and with D-TCSCs are shown in Table 5.Reactive power loss of line 36 (28-27) previously having highest value of 2.39 MVAR is now significantly reduced to 0.34 MVAR.

Table 5 MVAR Line Losses of 30-Bus System without TCSC's and with D-TCSCs

Branch #	MVAR Line Loss without D-TCSCs	MVAR Line Loss with D-TCSCs	Branch #	MVAR Line Loss without D-TCSCs	MVAR Line Loss with D-TCSCs
1	0.28	0.08	22	0.14	0.26
2	0.84	0.06	23	0.03	0.08
3	0.66	0.07	24	0.02	0.03
4	0.14	0.03	25	0.13	0.13
5	0.43	0.09	26	0.05	0.11
6	0.9	0.2	27	0.11	0.19
7	0.14	0.09	28	0.14	0.19
8	0.26	0.2	29	0.2	0.19
9	0.13	0.13	30	0.25	0.41
10	0.43	0.26	31	0.05	0.3
11	0.27	0.22	32	0.03	0.32
12	0.23	0.19	33	0.41	0.13
13	0	0	34	0.06	0.07
14	0.14	0.11	35	0.47	0.19
15	0.97	0.06	36	2.39	1.06
16	1.92	2.57	37	0.15	0.16
17	0.07	0.06	38	0.28	0.31
18	0.06	0.12	39	0.06	0.06
19	0.1	0.28	40	0.23	0.21
20	0.01	0.01	41	0.14	0.25
21	0.02	0.17			

From Table 5 and Figure 47, significant reduction in reactive power losses of lines 2, 6 and 15 can be noticed. Losses of line 16 increased from 1.92 MVAR to 2.57 MVAR and there is small increase in losses of lines 30, 31 and 32 but still the sum of reactive power line losses in the power system has been reduced from 13 MVAR to 10 MVAR after addition of D-TCSCs (as shown in Figure 48).

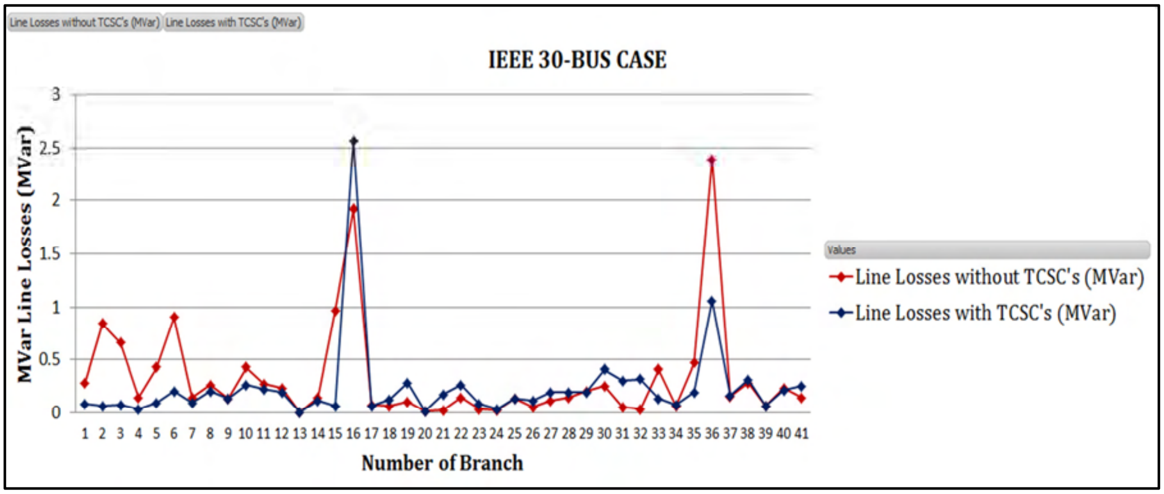


Figure 47 MVAR Line Losses of 30-Bus System without D-TCSCs and with D-TCSCs

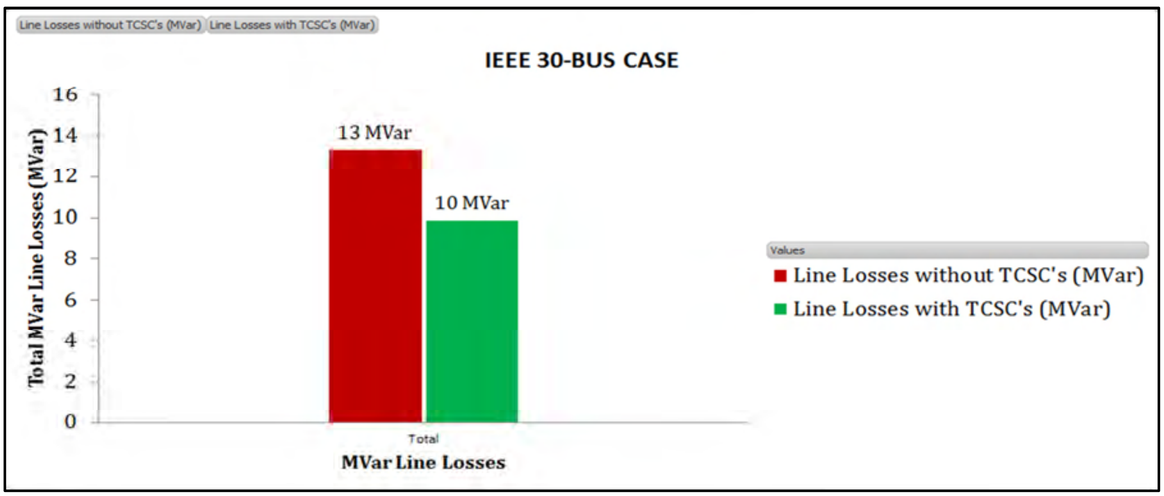


Figure 48 Total MVAR Line Losses of 30-Bus System without and with D-TCSCs

4.1.2.3 MW Line Losses

Active power dissipation in lines of 30-Bus power system without D-TCSCs and with D-TCSCs is shown in Table 6. The same has also been plotted in Figure 49 and sum of active power dissipation without D-TCSCs and with D-TCSCs has been shown in Figure 50. From Figure 49, it can be seen that significant reduction in active power dissipation across lines 2, 3 and 6 and some increase in power dissipation across lines 30, 31 and 32 after addition of D-TCSCs has been observed that is due to increase in power flow through these lines.

Table 6 MW Line Losses of 30-Bus System without D-TCSCs and with D-TCSCs

Branch #	MW Line Loss without D-TCSCs	MW Line Loss with D-TCSCs	Branch #	MW Line Loss without D-TCSCs	MW Line Loss with D-TCSCs
1	0.092	0.027	22	0.071	0.129
2	0.22	0.056	23	0.014	0.037
3	0.232	0.087	24	0.01	0.011
4	0.035	0.008	25	0.058	0.054
5	0.108	0.076	26	0.018	0.039
6	0.3	0.223	27	0.046	0.08
7	0.036	0.022	28	0.067	0.088
8	0.109	0.083	29	0.099	0.094
9	0.049	0.047	30	0.124	0.206
10	0.108	0.105	31	0.031	0.197
11	0	0	32	0.012	0.154
12	0	0	33	0.235	0.062
13	0	0	34	0.042	0.045
14	0	0	35	0.246	0.084
15	0	0	36	0	0
16	0	0	37	0.078	0.086
17	0.03	0.03	38	0.149	0.164
18	0.032	0.063	39	0.03	0.033
19	0.047	0.125	40	0.069	0.063
20	0.006	0.009	41	0.047	0.084
21	0.01	0.071			

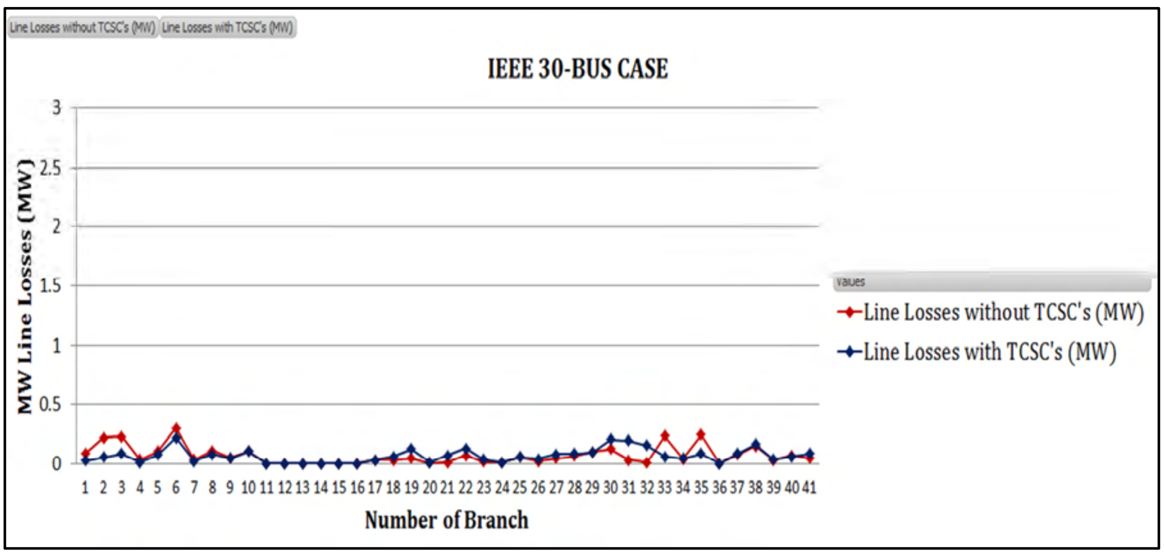


Figure 49 MW Line Losses of 30-Bus System without D-TCSCs and with D-TCSCs

However the overall active power dissipation of all lines in the power system is almost same as can be seen in Figure 50. Before addition of any D-TCSCs in the power system the total active power dissipation of lines is 2.86 MW and after addition of D-TCSCs in certain lines decrease in power dissipation is observed in few lines and increase in dissipation across few other lines at the same time but still the sum of active power dissipation is 2.74 MW that is close to previous value of 2.86 MW.

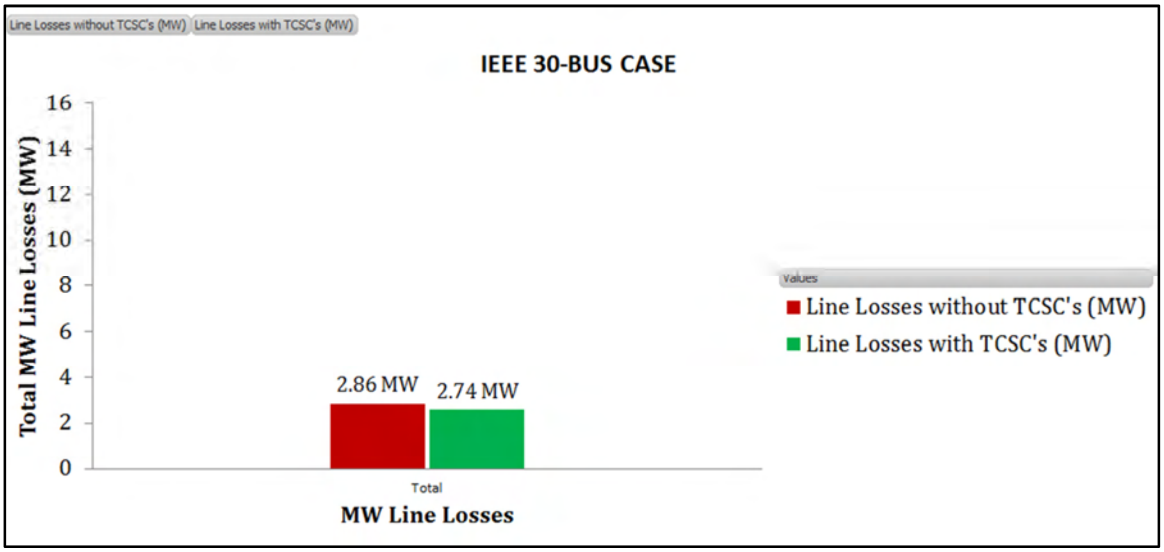


Figure 50 Total MW Line Losses of 30-Bus System without and with D-TCSCs

4.1.2.4 Generators MVAR Output

Reactive power generation of all six generators without D-TCSCs and with D-TCSCs is shown in Table 7. Total demand of reactive power by load and generation of reactive power from all generators before addition of D-TCSCs and after addition of D-TCSCs is shown in Figure 51. Demand of load is 107.2 MVAR and reactive power line losses without any D-TCSCs are 13.33 MVAR. These both are met by reactive power generation of 105.1 MVAR from all six generators, 0.2 MVAR of shunt injection and 15.2 MVAR of branch charging injection.

After addition of D-TCSC devices, demand of load is same as that of 107.2 MVAR but the reactive power line losses have been reduced to a value of 10 MVAR. So to meet this requirement, reactive power generation from all generators is reduced to 102 MVAR whereas reactive power injection from shunt and branch charging is same. Hence a reduction of 3 MVAR in reactive power generation of all generators has been observed with the addition of D-TCSCs.

Table 7 MVAR Generation of Generators without D-TCSCs and with D-TCSCs

Generator #	MVAR Generation by Generators Without D-TCSCs	MVAR Generation by Generators With D-TCSCs
1	-5.44	15.47
2	1.67	1.92
3	35.95	2.57
4	34.18	50
5	6.96	8.54
6	31.75	22.26
Total Generation	105 MVAR	101 MVAR

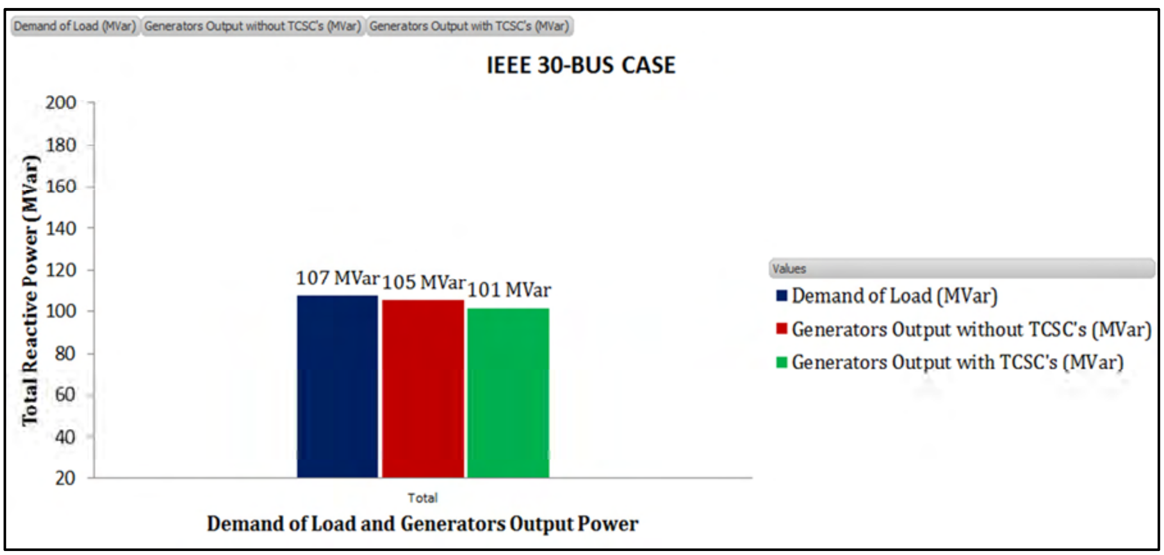


Figure 51 MVAR Load Demand and MVAR Output of Generators

4.1.2.5 Generators MW Output

Generation of active power from all six generators without D-TCSCs and with D-TCSCs is shown in Table 8. Sum of active power demand by load and generation of active power from all generators before addition of D-TCSCs and after addition of D-TCSCs is shown in Figure 52. Demand of load is 189.2 MW and active power line losses without any D-TCSCs are 2.86 MW. These both are met by active power generation of 192.1 MW from all six generators.

After addition of D-TCSC devices, active power demand of load and active power line losses of the system are the same. In order to meet the demand, active power generation from all generators remained 192 MW. Therefore no change in generation of active power has been observed with the addition of D-TCSCs.

Table 8 MW Generation of Generators without D-TCSCs and with D-TCSCs

Generator #	MW Generation by Generators Without D-TCSCs	MW Generation by Generators With D-TCSCs
1	41.54	0.01
2	55.4	71.41
3	16.2	40
4	22.74	8.09
5	16.27	26.41
6	39.91	46.02
Total Generation	192 MW	192 MW

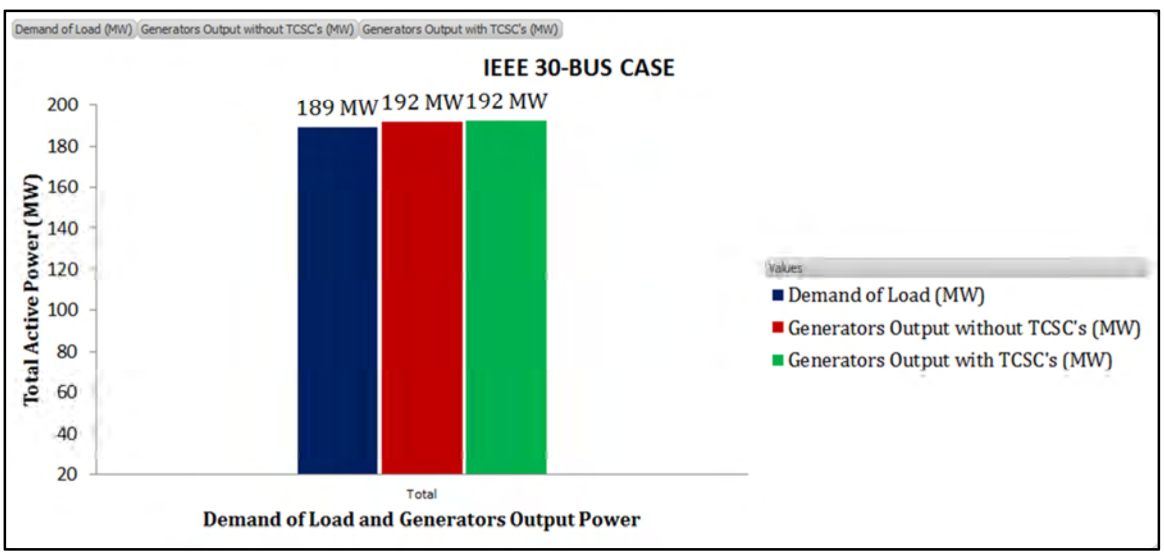


Figure 52 MW Load Demand and MW Output of Generators

5 CHAPTER

5.1 FAULT CURRENT CONSTRAINTS

Fault current is of much more importance in a power system. To protect a power system from any damage, fault current limits are reviewed regularly by the network operators. As to meet the increasing demand of power, new generation capacity is to be connected in the generation network that can entirely change the network characteristics and may lead to high currents during fault conditions that can even exceed the handling capability of installed switchgears and so may cause a great damage to the protection equipment. So, while expanding a power system to meet the demand of load, the greatest hurdle is the fault current limit of the installed switchgears.

In the methodology proposed, D-TCSC devices have been installed on different lines in the power system selected on the basis of reactive power losses. These devices can provide capacitive as well as inductive compensation. As discussed in chapter4, devices have been utilized mostly in their capacitive mode in the optimal power flow. The advantage can be taken from these installed devices by operating them in their inductive mode to limit the line currents during fault conditions. These devices can switch from either mode in micro seconds, so during the fault conditions a device can be set to its new mode through its communication module via power line communication or wireless communication or even itself when line current exceeds some threshold. The use of the device to limit fault current has been discussed under for 06-Bus Power System.

5.1.1 06-Bus Power System

Optimal power flow executed for 06-Bus power system having D-TCSCs installed on same lines as discussed in chapter 4. Value of compensation provided for each line by respective D-TCSC is shown in Table 9. It can be seen from the table that every line is being compensated capacitively. Fault current has been calculated for line 3-6 by setting bus No. 6 in fault condition. Fault current constraint has been added on line 3-6 of 06-Bus Power system to reduce its value. Optimal power flow has been re-executed to find out the optimal value for the compensation by the D-FACT device. Value of the compensation for each line has been shown in Table 9. It can be seen that only D-TCSC of line 3-6 has been switched to inductive mode while all the other D-TCSCs are set to zero by fault current constraints and the defined fault limit constraint has been respected.

Table 9 Values of D-TCSCs Before and After FLCs

Branch #	From Bus	To Bus	Value of D-TCSC Before FLC Added (pu)	Value of D-TCSC After FLC Added (pu)
9	3	6	-0.0479	0.0798
5	2	4	-0.0378	0
2	1	4	-0.0816	0
3	1	5	-0.1169	0
8	3	5	-0.0967	0
6	2	5	-0.1039	0

5.1.1.1 Line Fault Current at From Bus

Line fault current at from Bus has been shown by contour for before fault limit constraint and after fault limit constraint in Figure 53 and Figure 54 on a scale of 0 pu to 2.34 pu.

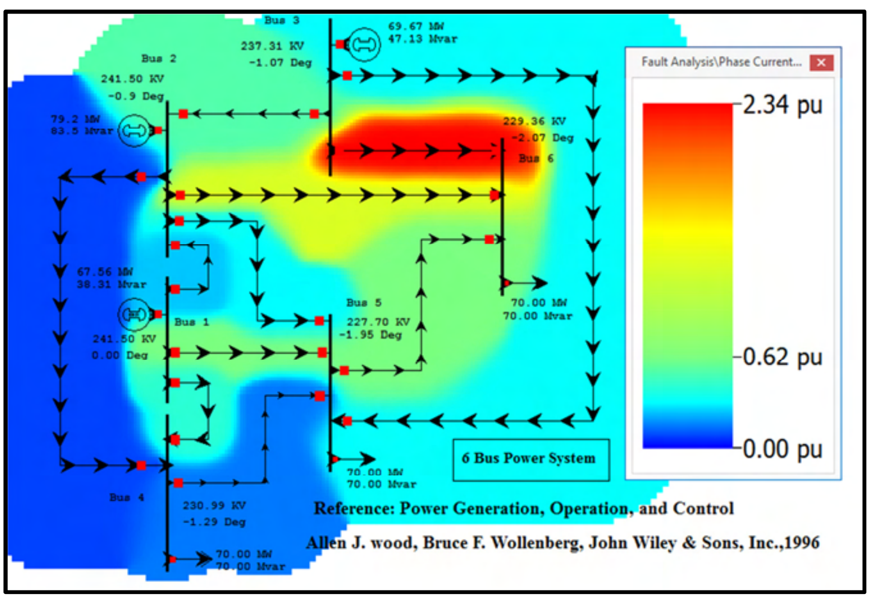


Figure 53 Line Fault Current at From Bus before FLC

It can be seen from the figures that before fault constraint the line 3-6 is having very high current flow that is 2.4 pu. After convergence of power flow to the optimal solution and setting the value of all D-TCSCs, it can be observed that the fault on line 3-6 has been decreased significantly. At the same time a minor decrease in current of line 3-5 can be seen in the contours. All other lines are carrying almost same current even after added fault current constraints whereas average pu line fault current has been decreased from 0.62 pu to 0.50 pu.

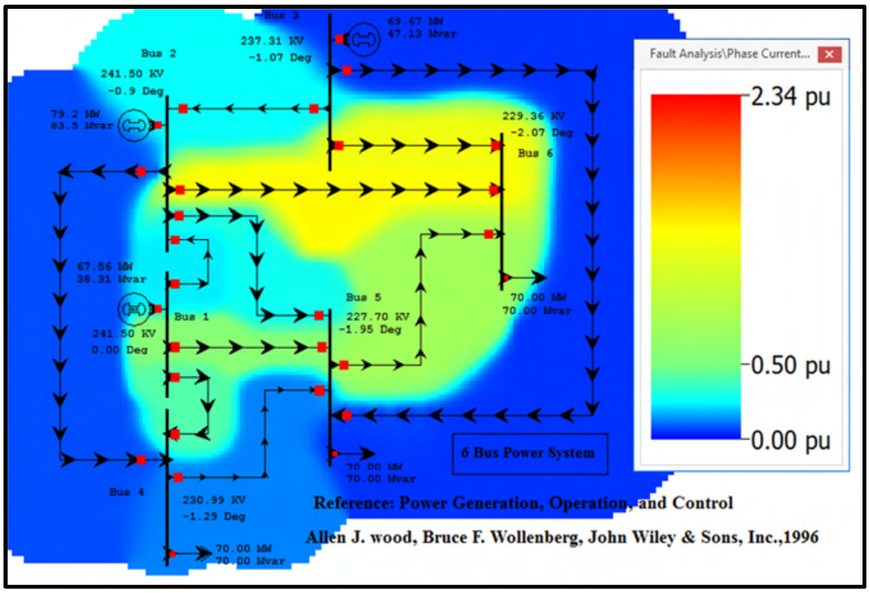


Figure 54 Line Fault Current at From Bus after FLC

5.1.1.2 Line Fault Current at To Bus

Line fault currents at ‘To’ bus before and after addition of fault limit constraints are shown in Figure 55 and Figure 56. These contours are also representing the same pattern as previously seen in line fault currents at ‘From’ bus. Significant reduction in line fault current at ‘To’ bus of line 3-6 is prominent and reduction in line fault current of line 3-5 has also been observed while all the other lines are having same fault currents.

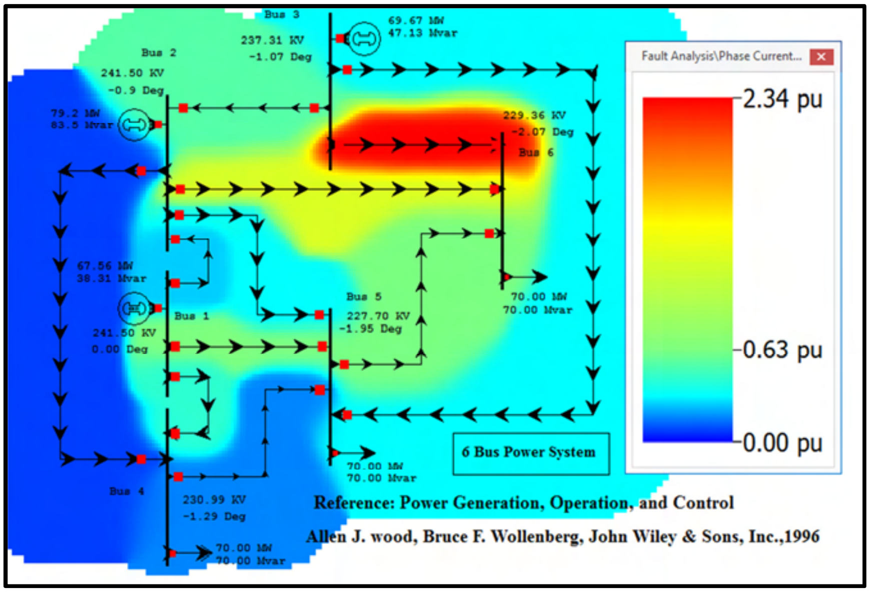


Figure 55 Line Fault Current at To Bus before FLC

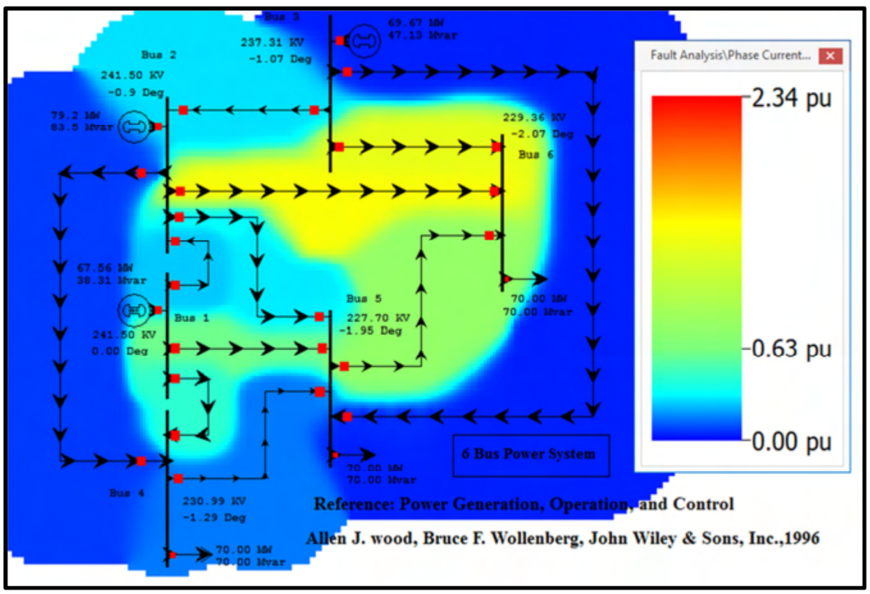


Figure 56 Line Fault Current at To Bus after FLC

5.1.1.3 Bus Fault Current

Bus 6 is set to fault and bus level fault for this bus is shown in Figure 57. The fault current for the said bus before fault current constraint was 4.2 pu. After addition of fault current constraint, bus level fault has been reduced to 3.9 pu. This fault current can further reduced by setting some other lines constrained those are connected with this bus.

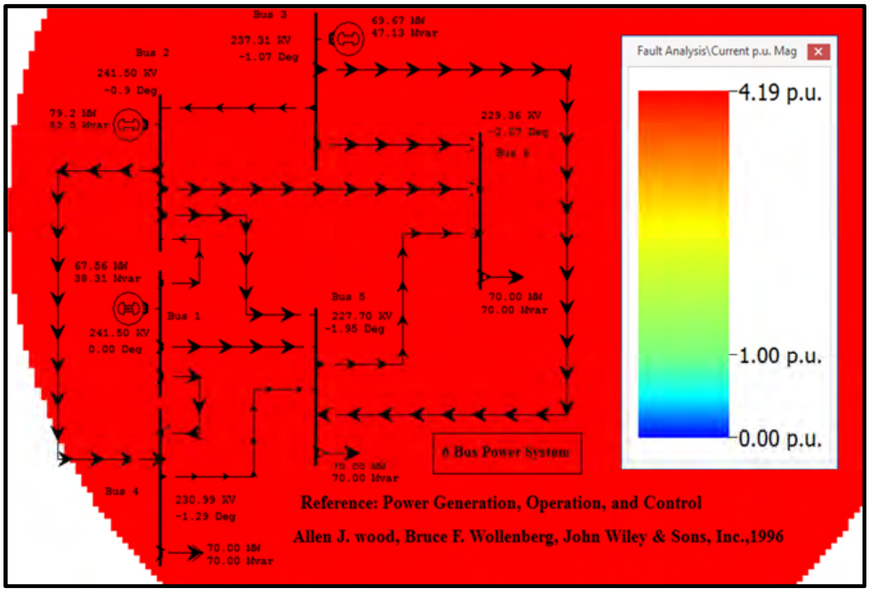


Figure 57 Bus Level Fault Current of Bus No. 6 before FLC

5.1.1.4 Post Fault Bus Voltages

Post fault bus voltages have been shown for before and after addition of fault constraint in Figure 58 and Figure 59.It can be seen that pu voltage magnitude of post fault voltage at buses 1 & 2 is slightly higher as compared to the case where there is no fault current constraint. Whereas post fault voltage of faulted bus is almost the same in both cases.

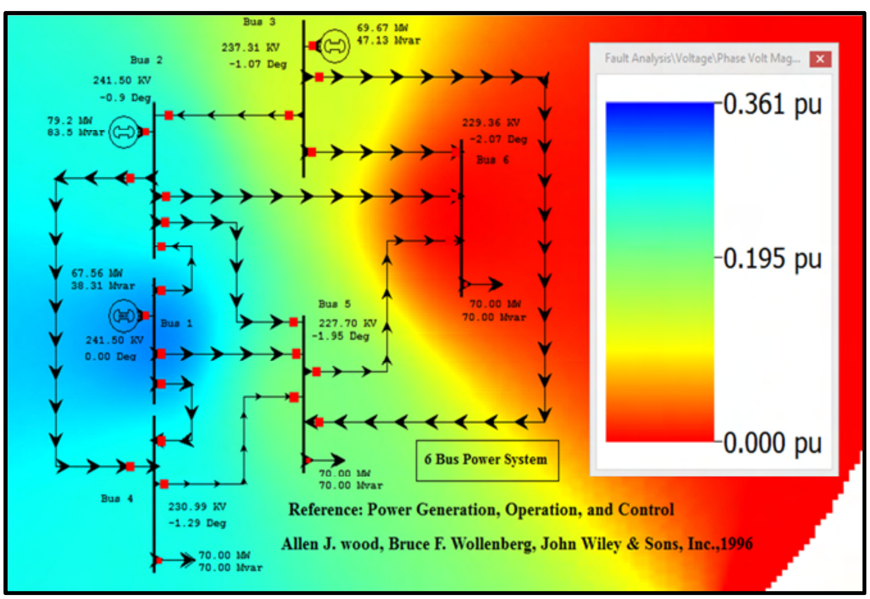


Figure 58 Post Fault Bus Voltages before FLC

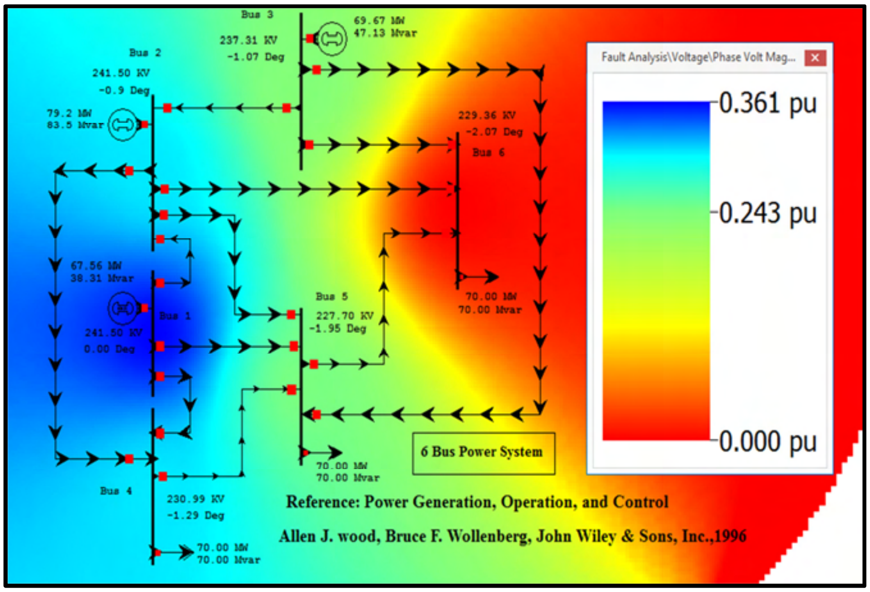


Figure 59 Post Fault Bus Voltages after FLC

6 CHAPTER

6.1 CONCLUSIONS

The research has been carried out with the aims to improve voltage profile of power system while reducing system losses and limiting fault current through a transmission line by using Distributed Flexible AC Transmission System (D-FACTS) controllers. The Distributed Thyristor Controlled Series Capacitor device (D-TCSC) is used in this research to control power flow in a power system. This device can provide series compensation and can be set to capacitive mode or inductive mode. The mode and level of compensation can be controlled autonomously or through communication module as device is able to communicate on power line carrier and wireless network. In this research, reactance of line where D-TCSC is installed is considered as one of optimal power flow variable and optimal value of the compensation has been found using Matpower / Knitro optimizer. The methodology has been tested on both IEEE 06-Bus power system and 30-Bus power system.

6.1.1 Goals Achieved

AC optimal power flow is executed on both test power systems. Then D-TCSCs are placed in those lines dissipating maximum amount of reactive power in the system. Improvement in voltage profile of power system is achieved in both cases. Voltage magnitude of buses is stabilized to ±2% of unity voltage magnitude. Reactive power line losses are reduced significantly and so is the sum of reactive power generation for both cases. At the same time, reduction in percentage of line limit used has been noticed with an increase in loadability of few lines of power system. No significant effect has been observed on active power dissipation across lines. Therefore active power generation in both cases is same before and after addition of D-TCSCs.

Furthermore, fault limit constraint has been defined and respected for line 3-6 to limit the fault current in case of any fault condition. Hence using the same devices, fault current has been restricted for a certain line. A linear constraint between the capacitive and reactive values provided by the same device has also been respected successfully using the proposed methodology. A significant reduction in fault current through a transmission line has been made possible using the D-TCSC in inductive mode.

6.1.2 Utilization of Research

Goals achieved by this research are improvement of voltage profile, reduction in reactive power line losses, increased loadability of lines, reduced percentage of line limit utilization and significant reduction in fault current through a transmission line. Keeping in view these achievements, the methodology can be used on transmission and distribution networks to improve the bus voltage magnitudes, to reduce reactive power line losses and to reduce fault currents through lines. Beside these benefits, loadability of even congested lines in the network can be increased further and percentage line limit utilization of the network can be reduced. As lines of distribution networks are more resistive than reactive, better results will probably be observed by applying the methodology on underground distribution networks (lines are more reactive as these are close to ground). The methodology can also be used in the power systems having shortfall of power generation as Matpower is capable of handling supply shortfall by modeling an import as a fixed injection together with a dispatchable load of equal size which bids at a high price [22].

6.1.3 Future Work

Distributed Thyristor Controlled Series Capacitor devices can also work in inductive mode and can switch from capacitive mode to its inductive mode in micro seconds. In this research the device has been used in its capacitive as well as inductive mode. However the inductive mode has only been utilized to restrict the fault current through a transmission line. By setting the constraint on the bus fault level currents, the same devices may be used to reduce the bus level fault currents without any additional cost. The device remains in the circuit even in short circuit conditions. So this feature of the device can be utilized in order to reduce fault levels on buses. Furthermore, financial analysis of the power system can be done by considering the cost of installation of devices, benefits of improvement in voltage profile, and savings from reduction in reactive power generation. Transient analysis of the network can be performed for insertion and desertion of compensation by the device.

7 CHAPTER

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