IMPROVEMENT OF POWER TRANSFER CAPABILITY USING TCSC

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BONAFIDE CERTIFICATE

Certified that this project report titled **IMPROVEMENT OF POWER TRANSFER CAPABILITY USING TCSC** is the bonafide work of **Mr. P.SURESHKUMAR** who carried out the research under my supervision. Certified further, that to the best of my knowledge the work reported herein does not form part of any other project report or dissertation on the basis of which a degree or award was conferred on an earlier occasion on this or any other candidate.

PROJECT GUIDE

HEAD OF THE DEPARTMENT

The Candidate with University Register No: [illegible] was examined by us in the project Viva-Voce examination held on [illegible]

INTERNAL EXAMINER

EXTERNAL EXAMINER

ABSTRACT

A Thyristor Controlled Series Capacitor (TCSC) method has been proposed to enhance the voltage stability by changing the reactive power distribution in the power system and which is a measure for controlling the power system oscillation and there by improving the system stability. In this project the steady state models of TCSC devices, the controllability and control range of power flow on the transmission line installed with single TCSC devices are analyzed. Time damping of the power system oscillation can be reduced through effective changes in line impedance. Through TCSC the effective line impedance can be controlled within a few milliseconds.

Generally the fault (Line to Ground) will be created in the transmission line. By placing TCSC in optimal location, so that real power, reactive power and voltage stability will be improved. Simulation result shows the advantages of using the modeling method when performing the power flow control in a power system involving the TCSC.

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INTRODUCTION

1.1. GENERAL

According to IEEE, FACTS, this is the abbreviation of Flexible AC TRANSMISSION Systems, is defined as follows, Alternating current transmission systems incorporating power electronics based and other static controllers to enhance controllability and power transfer capability. Since the "other static controllers" based FACTS devices are not widely used in current power systems, this thesis focuses only on the power electronics based FACTS device.

1.2 CONSTRAINTS IN A TRANSMISSION SYSTEM

In theory, a transmission system can carry power up to its thermal loading limits. But in practice, to reach the thermal limit, the system meets the following constraints:

i) Transmission stability limits
ii) Voltage limits
iii) Loop flows

With transmission stability limits are meant the limits of transmittable power with which a transmission system can ride through major faults in the system with its power transmission capability intact. With voltage limits are meant the limits of power transmission where the system voltage can be kept within permitted deviations from nominal, usually no more than 5-10%. The voltage is governed by a quantity named reactive power (Q). Q in its turn depends of the physical length of the transmission circuit as well as from the flow of active power. So, in simple terms, the longer the line and/or the heavier the flow of active power, the stronger will be the flow of reactive power, as a consequence of which the voltage will drop, until, at some critical level, the voltage collapses altogether.

Loop flows can be a problem as they are governed by the laws of nature which may not be coincident with the interests of man. This means that power which is to be sent from point "A" to point "B" in a grid will not necessarily take the shortest, direct route, but will go uncontrolled and fan out to take unwanted paths available in the grid, thereby generating additional losses and possibly also overloading of sections of neighbors′ power systems.

FACTS are designed to remove such constraints and to meet planners, investors and operators goals without their having to undertake major system additions. This offers ways of attaining an increase of power transmission capacity at optimum conditions, i.e. at maximum availability, minimum transmission losses, and minimum environmental impact. Plus, of course, at minimum investment cost and time expenditure.

1.3 FACTS CONTROLLERS

FACTS (Flexible Ac Transmission System) are the application of power electronic devices based systems used for AC transmission. FACTS devices can be effectively used for power flow control, loop flow control, load sharing among parallel corridors, voltage regulation, and enhancement of transient stability and mitigation of system oscillations. Given the nature of power electronics equipment, FACTS solution will be particularly justifiable in applications requiring one or more of the following qualities:

i) Rapid dynamic response
ii) Ability for frequent variations in output
iii) Smoothly adjustable output.

...ssion line is an important element of a power system utilized for transfer of real and reactive power from source to load. Under normal conditions, the voltage gradient does not dictate direction of power (real) flow along the transmission line. But when large reactive power (in proportion to real power) is to be transferred along a transmission line, the real power transfer may be due to voltage gradient. In such a situation the real power flows from lagging phase angle bus to leading phase angle bus. In view of the above discussion a general condition has been derived for a transmission line in terms of transmission line parameters.

New technology that can improve the capability of power delivery and effectively control power flow across specified lines has become necessary. In this dissertation TCSC modeling was carried out to increase the transfer capability of the transmission system. The TCSC was the second series FACTS controller to be developed. The primary uses of TCSC are to enhance the power system angle stability and to mitigate the sub-synchronous reactance by regulating real power and maximizing transient synchronizing torque between the interconnected power systems. However the inserted series capacitor also affects the reactive power distribution in the interconnected power systems. A rapid variable compensation was achievable through the use of a thyristor controlled reactor connected in parallel to a series capacitor. The state variable was the TCSC's firing angle which was combined with the nodal voltage magnitudes and angles of the entire network in a single frame of reference for a unified iterative solution through a Newton-Raphson method. The Newton-Raphson algorithm exhibits quadratic convergence regardless of the size of the network and the number of TCSC devices. Therefore, this device incorporates both continuous time dynamics and discrete, resulting in an involved analysis.

1.4 OUTLINE OF THE PROJECT

Chapter1 gives a general introduction about FACTS: constraints and its controllers.

Chapter 2 briefly describes the several ways of FACTS modeling and the basic structure of TCSC and their model.

In chapter 3, the implementation of FACTS in the power flow computation and their additional implementation for the devices.

In chapter 4, the methods for placing FACTS devices in optimal location and the enhancement of power systems security by FACTS devices.

In chapter 5, the mathematical formulation for TCSC and sensitivity calculation. In order to analyze the power system with respect to its dynamic performance, a simplified 14-bus network model was established in this chapter.

Simulation result for TCSC in transmission line during fault and after clearing the fault are demonstrated in chapter 6.

Chapter 7 deals with the hardware implementation for FACTS devices.

Chapter 8 concludes the project work.

CHAPTER 2

FACTS MODELING

In this Chapter mathematical models of FACTS are discussed. Firstly an overview of common modeling instruments is given and secondly the applied models are explained. The priorities for the models implemented in FlowDemo.net are applicability for the computation engine and clearness for the user.

2.1. FACTS MODELS

There are several ways of modeling FACTS, whereas the suitability of a model depends on the specific problem. Some basic modeling techniques are mentioned in the following.

2.1.1. Injection Model

The Injection Model describes the FACTS as a device that injects a certain amount of active and reactive power to a node, so the FACTS device is represented as a PQ-element Figure 2.1 shows the idea of interpreting a FACTS device as PQ-elements. If the FACTS model does not contain losses, the injected powers can be written as

$$Pij = UiUjBij \sin \delta ij \tag{2.1}$$

$$Pij = -Pij \tag{2.2}$$

$$Qij = U_i^2 Bij - UiUjBij \cos \delta ij \tag{2.3}$$

$$Qji = U_j^2 Bij - UiUjBij \cos \delta ji \tag{2.4}$$

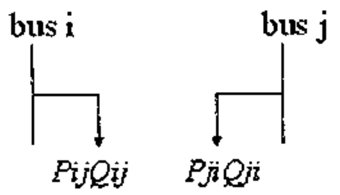


Figure 2.1 Injection Model

Whereas only the FACTS (no other elements) is connected between bus *i* and bus *j*. *Pij* and *Pji* represent active power flow; *Qij* and *Qji* are reactive power values. The transmission angles are

$$\delta ij = \theta i - \theta j = \angle Ui - \angle Uj \quad (2.5)$$

$$\delta ji = -\delta ij \quad (2.6)$$

Since this model uses PQ-elements to describe the FACTS, it can be implemented in a Newton-Raphson computation like PQ-loads. The Injection Model does not contain internal information about the device, i.e. it is independent from the internal design of the FACTS.

2.1.2. Total Susceptance Model

This model interprets the FACTS as a shunt (for shunt compensation) or series element (for series compensation) with varying susceptance *B*. Due to (2.1)-(2.6) the power flow through the FACTS depends on *B*, *Pij* and *Qij* = *f*(*B*). Figure 2.3

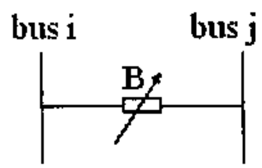
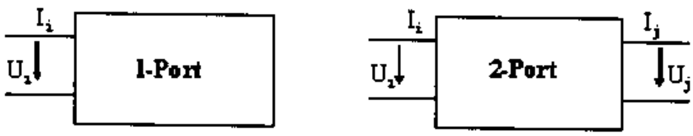


Figure 2.2 Total Susceptance Model

Shows a 1-port and a 2-port black box. In network analysis every n-port is represented by the impedance matrix which can be stated from the T or Π circuit model of the network element. Inserting the variable B in the 1- and 2-port models for shunt and series elements leads to the 1-port matrix model for the shunt connected element:

$$[Ii]-[jBij][Ui]=[0] \tag{2.7}$$



(a) (b)

Figure 2.3 1-Port(a) and 2-Port(b) Element

The 2-port model for the series element can be stated as:

$$\begin{bmatrix} Ii \\ Ij \end{bmatrix} - \begin{bmatrix} -jBij & jBij \\ jBij & -jBij \end{bmatrix} \begin{bmatrix} Ui \\ Uj \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \tag{2.8}$$

Since it is well known how to implement the 1-port and 2-port models in a power flow computation, this model is proper for a power flow computation with Newton-Raphson. Like the Injection Model, the Total Susceptance Model does not describe the internal design of the FACTS. It does not contain the dependence of B from any internal value, for example firing angle.

2.1.3 Firing Angle Model

The Firing Angle Model includes the dependence of the FACTS impedance or power values from the variable firing angles of semiconductor switches. The firing angle is now considered as a state variable, so that $B-1ij = Xij = f(a,XL,XC)$ and $Pij,Qij =$

$f(\alpha,XL,XC)$. Such a function $f(\alpha,XL,XC)$ can be inserted in the Injection Model as well as in the Total Susceptance Model. With this extended model the user can influence powers by changing firing angles of the valves.

With the Firing Angle Model we consider the internal circuit as well as values which affect the power flow through the device, like capacitance, reactance and especially the firing angle. A major difference between this model and the models mentioned above is that the Firing Angle Model describes the FACTS internal design.

2.2. IMPLEMENTED MODELS

After having a look on different modeling techniques in Section 2.1 we will now discuss which and how models are implemented in the computation engine. For each type of regulation the models are nested in different ways with respect to the firing angle.

Power-Regulation: The injected powers are set by the user, so the injected load(s) is (are) given. After the Newton-Raphson power flow computation the apparent susceptance of the FACTS can be determined from the node voltage and the power value. In the last step the fire delay angle is computed from the apparent susceptance by adopting the Firing Angle Model (see Section 2.1.3).

Voltage-Regulation: The desired node voltage is given; the injected powers are results of the power flow computation. After determining the total susceptance of the device from the voltage and the power value, the fire delay angle is calculated.

Angle-Regulation: The total susceptance can be determined from the user-defined fire delay angle and the reactance of the capacitor and the reactor. Afterwards the device is implemented in the power flow computation like a shunt or series element (TCSC). The injected loads are result from the computation.

2.3. THYRISTOR CONTROLLED SERIES CAPACITOR (TCSC)

TCSC is a capacitive reactance compensator, which consists of a series capacitor bank shunted by a Thyristor Controlled Reactor (TCR) in order to provide a smoothly variable series capacitive reactance. The TCSC is based on thyristor without the gate turn-off capability. It is an alternative to SSSC and like an SSSC; it is a very important FACTS controller. A variable reactor such as a Thyristor-Controlled Reactor (TCR) is connected across a series capacitor. When the TCR firing angle is 180 degrees, the reactor becomes non-conducting and the series capacitor has its normal impedance. As the firing angle is advanced from 180 degrees to less than 180 degrees, the capacitive impedance increases. At the other end, when the TCR firing angle is 90 degrees, the reactor becomes fully conducting, and the total impedance becomes inductive, because the reactor impedance is designed to be much lower than the series capacitor impedance. With 90 degrees firing angle, the TCSC helps in limiting fault current. The TCSC may be a single, large unit, or may consist of several equal or different-sized smaller capacitors in order to achieve a superior performance.

The scheme of a Thyristor-Controlled Series Capacitor is given in Fig. A Para-meter to describe the TCSC main circuit is λ which is the quotient of the resonant frequency and the network frequency resulting in

$$\lambda = \sqrt{\frac{-X_C}{X_L}} \tag{2.9}$$

Where $X_C = -1/\omega c$ and $X_L = \omega L$

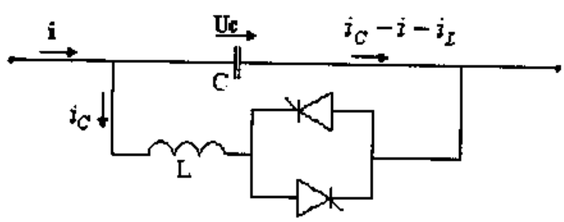


Figure 2.4 Thyristor-Controlled Series Capacitor (TCSC)

The operating modes of a TCSC are characterized by the so-called boost factor

$$K_B = X_{TCSC} / X_C \qquad (2.10)$$

Where X_{TCSC} is the apparent reactance

1. Blocking mode: The thyristor valve is not triggered and the thyristors are kept in no conducting state. The line current passes only through the capacitor Bank (XTCSC = XC). Thus, the boost factor is equal to one. In this mode the TCSC performs like a fixed series capacitor.

2. Bypass mode: The thyristor valve is triggered continuously and therefore the Valve stays conducting all the time. The TCSC behaves like a parallel connection Of the series capacitor and the inductor. As

$$X_{TCSC} = \frac{X_L X_C}{X_L + X_C} = \frac{-X_C}{1-\lambda^2} \qquad (2.11)$$

The voltage is inductive and the boost factor is negative. When it is considerably Larger than unity the amplitude of X_c is much lower in bypass than in blocking mode. Therefore, the bypass mode is utilized to reduce the capacitor stress during faults

3. Capacitive boost mode: If a trigger pulse is supplied to the thyristor having forward voltage just before the capacitor voltage crosses the zero line a capacitor discharge current pulse will circulate through the parallel inductive branch. The discharge current pulse adds to the line current through the capacitor bank. It causes a capacitor voltage that adds to the voltage caused by the line current. The capacitor peak voltage thus will be increased in proportion to the charge

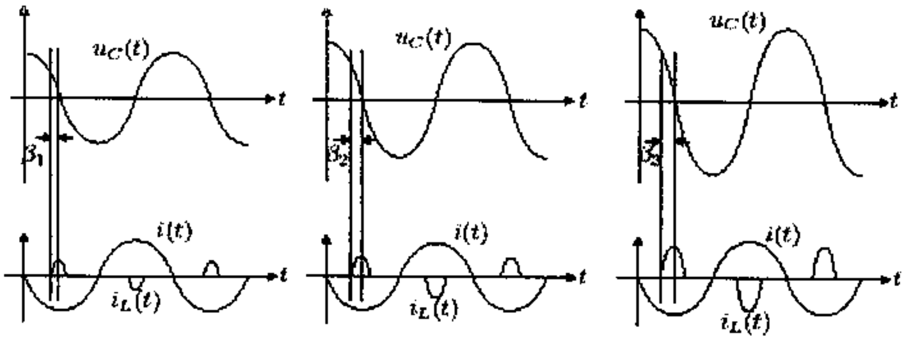


Figure 2.5 Waveforms at various boost factors in capacitive boost mode

that passes through the thyristor branch. The charge depends on the conduction angle β Fig. For the boost factor, the mathematical formula is (without giving the derivation)

$$K_B = 1 + \frac{2}{\pi}\frac{\lambda^2}{\lambda^2 - 1}\left[\frac{2\cos^2\beta}{\lambda^2 - 1}(\lambda\tan\lambda\beta - \tan\beta) - \beta - \frac{\sin 2\beta}{\beta}\frac{dy}{dx}\right] \tag{2.12}$$

Due to the factor tan (λβ) this formula has an asymptote at β_∞. The TCSC operates in the capacitive boost mode when $0<\beta<\beta_\infty$ an example boost factor versus conduction angle characteristic is given in Fig.

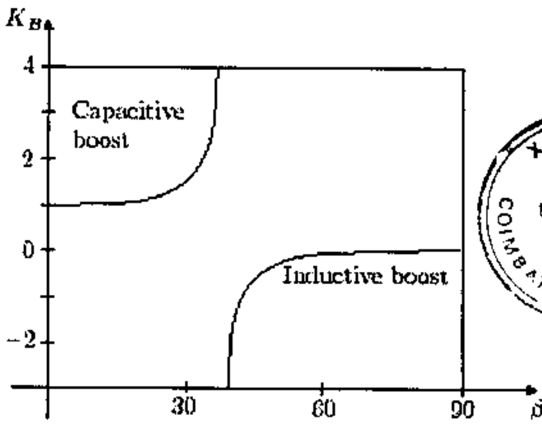


Figure 2.6 Boost factor versus conduction angle

4. Inductive boost mode: If the conduction angle is increased above the mode changes from conductive to inductive boost mode Fig. In the inductive boost mode, large thyristor currents may occur. The curves of the currents and the voltage for three deferent conduction angles are given in Fig. The capacitor voltage waveform is very much distorted from its desired sinusoidal shape. Because of this waveform and the high valve stress, the inductive boost mode is less attractive for steady state operation.

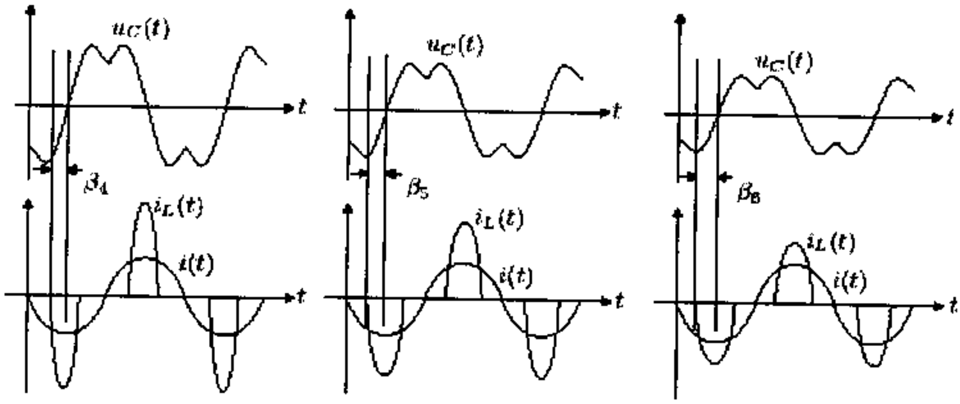


Figure 2.7 Waveforms at various boost factors in inductive boost mode

Because a TCSC is based on the same idea as the TSSC, namely to introduce additional reactance's, the characteristics of the transmitted power versus transmission angle looks alike the one of the TSSC in Fig and also the $\partial p/\partial k$ is the same Fig.

The device is usually designed to directly control line current, but various strategies can be used to control line impedance or power flows, damp oscillations. The limits on the firing angle α for the TCSC controller, as there is a resonance region where the controller becomes an open circuit and hence, it must be avoided in a series connection. Furthermore, the controller is designed to mainly operate in the capacitive region in steady state, to reduce harmonic pollution of the current waveforms. Thus $\alpha_T<\alpha<180^\circ$, where α_T corresponds to the resonant point (this value depends on the ratio X_C/X_L).

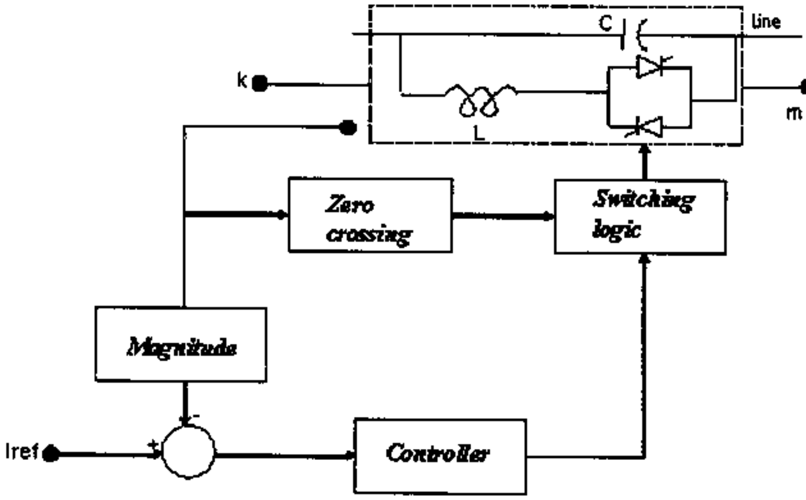


Figure 2.8 Structure of TCSC

The following fundamental frequency, steady state model is used here to model this controller

$$P+V_kV_mB_C\sin(\theta_k-\theta m) = 0 \quad (2.13)$$

$$-V_k^2 B_c+V_kV_mB_c\cos(\theta_k-\theta_m)-\theta_k = 0 \quad (2.14)$$

$$-V_m^2 B_c+V_kV_mB_c\cos(\theta_k-\theta_m)-\theta_m = 0 \quad (2.15)$$

$$\begin{aligned} &B_c-\pi(K_x^4 - 2 K_x^4 +1) \cos Kx(\pi-\alpha) / \\ &[X_c(\pi K_x^4 \cos K_x(\pi-\alpha) \\ &-\pi \cos Kx(\pi-\alpha)-2 K_x^4 \alpha \cos Kx(\pi-\alpha) \\ &+2\alpha K_x^2 \cos Kx(\pi-\alpha) - K_x^4 \sin 2\alpha \cos K_x(\pi-\alpha) \\ &+ K_x^2 \sin 2\alpha \cos K_x(\pi-\alpha) -4 K_x^3 \cos^2 \alpha \sin K_x(\pi-\alpha) \\ &-4 K_x^2 \cos\alpha \sin\alpha K_x(\pi-\alpha)]=0 \end{aligned} \quad (2.16)$$

$$\sqrt{P^2+Q_k^2} - I V_k = 0 \quad (2.17)$$

Where $V_k \angle \theta_k$ and $V_m \angle \theta_m$ are the terminal phasor voltages of the controller; Qk and Qm are the reactive power injections at both controller terminals; P and I are the active power and current flowing through the controller. Bc is the equivalent susceptance of the

TCR-fixed-capacitor combination; Xc and X_l are the fundamental frequency reactance of C and L; and $kx = \sqrt{Xc/XL}$.

2.3.1 TCSC Model

The TCSC is a series connected TCR in parallel with a capacitor. For the injected

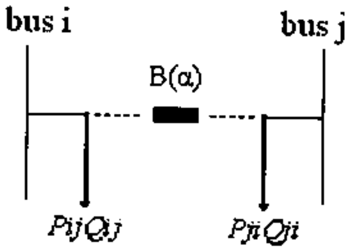


Figure 2.9 TCSC Model

power values of the TCSC at bus *i* and bus *j* the equations (2.1)-(2.6) are used. The equation leads to the transmitted active power

$$Pij = Ui\,Uj \left(B_L \frac{\pi - 2\alpha - \sin 2\alpha}{\pi} + B_C \right) \sin \delta ij \tag{2.18}$$

Since the model does not consider any active power losses in the TCSC we get the same absolute value (but due to the reference system with a different sign) on the other bus of the TCSC:

$$Pji = -Pij \tag{2.19}$$

Since losses in lines are usually not neglected, this equation is just valid for the TCSC element but not for a combination of a TCSC with lines. Because the TCSC is a reactive element the reactive power values are not equal on both nodes, they can be stated as

$$Qij = Ui \left(B_L \frac{\pi - 2\alpha - \sin 2\alpha}{\pi} + B_C \right) \left(Ui - Uj \cos \delta ij \right) \tag{2.20}$$

$$Qji = Uj \left(B_L \frac{\pi - 2\alpha - \sin 2\alpha}{\pi} + B_C \right) \left(Uj - Ui \cos \delta ji \right) \tag{2.21}$$

If the circuit is in resonance state, the expression in the big brackets of (2.24) and (2.25) gets close to zero. Assuming a certain (desired) power flow $Pij + jQij$ one can recognize that this would cause very high bus voltages that could endanger the TCSC.

CHAPTER 3

IMPLEMENTATION OF FACTS IN THE POWER FLOW COMPUTATION

3.1. TCSC

For the Thyristor Controlled Series Capacitor two types of regulation are implemented. The first one is the control of the active transmitted power P, the second is to set the fire delay angle α. Depending on the control mode, the TCSC is implemented as loads on the connected busses or as a line between them. For this reason the TCSC matrix which includes all TCSC information is split and the TCSC elements are embedded in the element matrices of loads and lines. The computation starts with this additional row in the load and line matrices. After it is finished the results are assigned to TCSC, lines and loads.

3.1.1 Active Power Regulation

P-regulated TCSC means that the user defines the active power that should be transmitted from bus i to bus j, whereas the reactive powers, the equivalent susceptance and the firing angle are unknown.

Eliminating B from (2.1)-(2.4) gives the injected reactive power values as functions of the specified value P and the complex node voltages:

$$Qij = \frac{Pij}{\sin \delta ij}\left[\frac{Ui}{Uj} - \cos \delta ij\right] \tag{3.1}$$

$$Qji = \frac{Pij}{\sin \delta ij}\left[\frac{Uj}{Ui} - \cos \delta ji\right] \tag{3.2}$$

With this equations the TCSC can be handled like two loads $Pij + jQij$ at bus i and $Pij + jQji$ at bus j.

Using (3.2) and (3.3) to obtain the reactive power values, we have to consider that the node voltages are not known before the power flow computation and that they will vary with every iteration of the Newton-Raphson algorithm. Therefore Qij and Qji have to be recalculated after every iteration step. When the Newton-Raphson computation is finished, the apparent susceptance of the TCSC is found by transforming (2.18):

$$B = \frac{Pij}{Ui\,Uj \sin \delta ij} \qquad (3.3)$$

The fire delay angle α can be determined from the equivalent susceptance $B = f(\alpha)$, XL and XC as explained in 3.2.1.

3.1.2 Firing Angle Regulation

The angle-regulated TCSC is treated like a line with variable reactance X. After the apparent susceptance B of the TCSC circuit is computed, the line impedance can be set to $X = B-1$. This TCSC, which is now handled like a line with $Z = jB-1$ is added in the line matrix and the computation is started. The result contains the active and reactive power values.

3.1.3 Resonance Protection and Angle Limits

Every TCSC circuit has a resonance point where the total impedance gets infinite high and, assuming a certain current, the voltage between the TCSC busses gets infinite high too. To protect the TCSC elements from overvoltage, real circuits include a Metal Oxide Varistor (MOV) in parallel to the capacitor and the TCR. Another more preventative kind of overvoltage protection is to avoid a certain band of the firing angle where resonance would put the circuit at the risk of overvoltage. For this reason the user is not allowed to set the fire delay angle in an area which is close to the resonance angle α_{res}, the 'safety margin' $\Delta\alpha$ must be kept. Since the user usually does not know the resonance angle of the circuit the fire delay angle αres that would cause resonance is computed. Afterwards it is checked and, if necessary, the angle is corrected automatically

- If $\alpha res - \Delta\alpha < \alpha \leq \alpha res$ it is set to $\alpha = \alpha res - \Delta\alpha$
- If $\alpha res < \alpha < \alpha res + \Delta\alpha$ it is set to $\alpha = \alpha res - \Delta\alpha$

These are the resonance limits for the fire delay angle. Additional limits result from the maximum and minimum firing delay, this is

$$0° \geq \alpha \geq 90°$$

and corrected, if the user defines the firing angle outside this range. In order to inform the user about any automatically modification of input data, a message is sent to the GUI if corrections have been done.

3.1.4 Power Limits

Real generators are not able to deliver unlimited power. The mechanical and electrical design of a machine leads to limits for active and reactive power. If a generator reaches such a power limit, the control unit keeps the value on a constant level (limit) independent from the power demand in the system. This fact has to be considered and implemented in the computation software. In this borders were checked after the Newton-Raphson algorithm converged. If limits were violated, the element values were set to these boundary values and the computation was started again. This procedure is now integrated in the Newton-Raphson algorithm. Whenever the absolute values of the disturbance vector are below the tolerance value the limits are checked. If there are any violations the exceeded values are set to their limits and the computation continues. If no limits were violated the loop ends and the computation itself is finished.

3.2. ADDITIONAL IMPLEMENTATIONS

3.2.1. Determination of the Fire Delay Angle

For P-, Q- and V-regulated devices, the equivalent susceptance is determined after the power flow computation.

Due to the fire delay angle α is a function of the TCR's apparent susceptance B, the susceptance of the reactor BL and the capacitance BC. If these three values are known it is possible to determine α from a nonlinear implicit equation in the form of

$$g(\alpha) = 0 \qquad (3.4)$$

Transforming leads to

$$g(\alpha) = B - \left(B_L \frac{\pi - 2\alpha - \sin 2\alpha}{\pi} + B_C \right) = 0 \qquad (3.5)$$

This equation can be solved with the method of Newton-Raphson. It uses a Taylor series approach, therefore it is necessary to find the derivation

$$\frac{\partial g(\alpha)}{\partial \alpha} = \frac{\partial}{\partial \alpha}[B - [B_L \frac{\pi - 2\alpha - \sin 2\alpha}{\pi} + B_C]] \qquad (3.6)$$

that results in

$$\frac{\partial g(\alpha)}{\partial \alpha} = \frac{2B_L}{\pi}(1 + \cos 2\alpha) \qquad (3.7)$$

The determination of the fire delay angle is implemented with a Newton-Raphson algorithm in Matlab. The function is used to determine the resonance firing angle *ares* before the power flow computation gets started and to determine the firing angle after the power flow computation of P-, Q- or V-regulated devices has finished.

3.2.2 Incremental Changes of TCSC

Whenever the user changes only one value of the network, for example a load value, the program does not start a completely new computation of the whole network. Only the changed value is sent from the client to the computation engine and the Newton-Raphson algorithm starts taking the former results as initial values. The intention behind this procedure is to increase the computation speed, especially when the client works in run-mode and the user changes a value by clicking on a puls/minus-button of an element. For TCSC this incremental change are implemented for changes of the target values P, Q, U and α. If the control mode of a FACTS element is changed, the power flow computation is started from the beginning

The implementation allows to do incremental changes in two steps:

1. Several declarations of variables which identify the changing element and the setting of the new target value have to be done.
2. A script which searches for the changing element and replaces the old value with the new value before it runs the load flow computation has to be called.

CHAPTER 4

OPTIMAL POWER FLOW USING SUITABLY PLACED FACTS DEVICES IN COMPETITIVE POWER MARKET

4.1. METHODS FOR OPTIMAL LOCATIONS OF FACTS DEVICES

Due to considerable cost of FACTS devices, it is important to ascertain the suitable locations fir placement in the system. There are several methods for finding optimal locations of FACTS devices in both vertically integrated and unbounded power systems. Using a FACTS device to reduce the real power loss in a particular line as an objective of device location may, however, increase the total system loss and/or may increase over loading elsewhere .Reduction in the total system active power loss will reduce or eliminate unwanted loop flows but there is no guarantee that lines will not be overloaded though this is unlikely in the absence of congestion.

Congestion in a transmission system, whether vertically organized or unbundled, cannot be permitted except for very short duration, for fear of cascade outages with uncontrolled loss of load. If there is no congestion, the placement of FACTS devices, from the static point of view, can be decided on the basis of reducing losses but this approach is inadequate when congestion occurs. A method based on the real power performance index (PI) can be considered due to security and stability reasons. The severity of the system loading under normal and contingency cases can be described by a real power line flow performance index, as given below

$$PI = \sum_{m=1}^{N} \frac{Wm}{2n} \left(\frac{P_{lm}}{P_{lm}^{\max}} \right)^{2n} \tag{4.1}$$

Where P_{lm} is the real power flow and P^{max} is the rated capacity of linr-m, n is the exponent and Wm a real non-negative weighting coefficient which may be used to reflect the importance of lines.

PI will be small when all the lines are with in their limits and reach a high value when there are overloads. Thus, it provides a good measure of security of the line overloads for a given state of the power system. Most of the work on the contingency selection algorithms utilize the second order performance indices, which, in general, sufferers from masking effects. The lacks of discrimination , in which the performance index for a case with on huge violation , is known as masking effect .By the most of the operational standards, the system with one huge violation is much more severe than that with many small violations . Masking effect to some extent can be avoided by using higher order performance indices, than is $n \geq 1$. However, in this study, the value of exponent has been taken as 2 and w_i=1.0.

4.2. OPTIMAL POWER DISPATCH WITH FACTS DEVICES

Transmission dispatch in an unbundled environment will be a mix of pool and bilateral/multilateral transactions. The optimal dispatch will be the delivery all bilateral and multilateral transactions in full and to supply of all pool demand at least cost without any security violations. This case can be termed the normal condition. Mathematically the normal dispatch problem can be written as,

$$MinF(x,u,p) \quad (4.2)$$

Subject to

$$h(x,u,p) = 0 \text{ (equality constraints)} \quad (4.3)$$

$$g(x,u,p) \geq 0 \text{ (inequality constraints)} \quad (4.4)$$

where x = state vector i.e. $V, \delta, V_T, \phi_T, Iq$

u = control parameters viz. P_{gi}, Q_{gi}

p = fixed parameters viz. P_{di}, Q_{di}

4.3. CONGESTION MANAGEMENT BY OPTIMIZING FACTS DEVICE LOCATION

Existence of network constraints dictates the finite amount of power that can be transferred between two points on the electric grid. In practice, it may not be possible to deliver all bilateral and multilateral contracts in full and to supply all demand at least cost due to violation of operating constraints such as voltage limits and line over-loads (congestion). Congestion in a transmission system, whether vertically organized or unbundled, cannot be tolerated except briefly, since this may cause cascade outages with uncontrolled loss of load. Congestion can be relieved, sometimes, by cost-free means such as outage of congested branches (line or transformers), operation of FACTS devices and operation of transformer taps. It is not always possible by cost-free means and some non-cost-free congestion control methods such as re-dispatch of generation and curtailment of pool loads and/or bilateral contracts are exercised.

FACTS devices could be used to control the power flow in lines by changing their parameters, so they can be applied to relieve congestion in the deregulated market. There are several methods for finding optimal locations of FACTS devices in both vertically integrated and unbundled power systems. The sensitivity approach based on line loss has been proposed for placement of series capacitors, phase shifters and static VAR compensators. Other works in optimal power flow with FACTS devices have used optimization with different objective functions. At the same time, the optimal locations of FACTS devices are obtained by solving the economic dispatch problem plus the cost of these devices making the assumption that all lines, initially, have these devices. In the presence of bilateral/multi-lateral contracts it would be difficult to use this objective.

4.4. ENHANCEMENT OF TOTAL TRANSMISSION CAPABILITY BY FACTS DEVICES

In deregulated power systems, total transfer capability (TTC) analysis is presently a critical issue either in the operating or planning because of increased area interchanges among utilities. TTC can be calculated by solving optimal power flow (OPA) algorithms .To compute, for a given system state .the TTC from one location (bus-i) to another location (bus-j), the following procedure is used:

(i) Obtain base case by running the OPF for the given system load and generation and Obtain the flows on the selected transmission path between the two buses.

(ii) Connect a generator of high capacity at bus-i. Connect a generator and a sink (load) at bus-j of the same capacity as of generator at bus-i.

(iii) Set the higher cost of generator at bus-j than at bus-i. By fixing the other generation at the base level, run OPF to obtain the generation at bus-i.

(iv) The output of the generator at bus-I will be the TTC.

This approach can be used to calculate the TTC with and without FACTS devices.

4.5. ENHANCEMENT OF POWER SYSTEMS SECURITY BY FACTS DEVICES

Stressed power system, either due to increased loading or due to severe contingencies, often lead to situation where system no longer remains in the secure operating region. Under these situations, it is primary objective of the operator to apply control action to bring the power system into the secure region. Any delay or unavailability of suitable control, the system may become unstable. The security of power system can be defined as its ability to withstand a set of severe but credible contingencies and to survive transition to an acceptable new steady state condition. In present day power system, there will be an increase in number of situations where power flow equations have either no real solution (unsolvable) or solution with violating operating limits such as voltage limit (insecure case), particularly, in contingency analysis and planning applications.

Since insecure case often represent the most severe threats to secure system operation, it is important that the FACTS devices should enhance the system security along with the other control devices. The possibility of controlling power flow in an electric power system without generation rescheduling or topological changes can improve the performance considerably. The increased interest in these devices is essentially due to increased loading of power systems, combined with deregulation of power industry, and motivates the use of power flow control as a very cost-effective means of dispatching specified power transactions.

FACTS devices can play very important role in power system security enhancement. Due to high capital investment, it is necessary to locate these devices optimally in the power system. A suitable approach can be used based on the sensitivity analysis on FACTS device control parameters with respect to reduction in real power flow performance index to enhance the security of the power system.

4.6. IMPACT OF FACTS DEVICES ON TRANSMISSION PRICING

Transmission pricing has been an important issue in the ongoing debate about power system restructuring and deregulation. Purpose of pricing is to recover cost of transmission, encourage efficient use and investment. The utilizes location based pricing concepts and has suggested a nonlinear programming problem formulation to determine real and reactive power prices, with an objective to maximize the net social welfare within the system constraints. In the power system, it is always desirable to install the reactive power sources near to the loads in order to minimize its flow in the network. Large flow of reactive power, in present day power system, has necessitated introducing some kind of pricing to restrict its flow and forcing to improve the system performance. Though, there is some debate regarding the viability of reactive power prices, any pricing scheme will likely to be based on spot pricing. Location based marginal cost pricing is most complicated but accurate pricing method. It determines the transmission prices for power at each bus in the system. Wheeling rate for any transaction between two buses is interpreted as difference in these costs. Total wheeling charge includes transmission charges, additional facilities cost and transmission network cost.

Due to number of environmental and economic constraints to build new power plants and transmission lines, power systems are forced to operate closer to their full capacity. To increase the system control capability, devices based on power electronics such as Flexible AC Transmission System (FACTS) are being used. Introduction of these devices and their optimal allocation improve the system stability, security and reliability. Limited efforts have been made to study the impact these devices on transmission charges. FACTS devices shown ability to change the production cost and their impact on transmission charges. The effect of FACTS devices on transmission charge varies according to the pricing methodology adopted. FACTS devices have ability to reduce the overall operating cost and the impact on transmission pricing.

The conclusion of impact of FACTS devices on transmission pricing the can be drawn:

(i) By including FACTS devices in the OPF problem, significant reduction in both total real power loss and total reactive power loss is obtained. The FACTS devices also help in reducing the generation cost in the deregulated energy market.

(ii) Implementation of FACTS devices into the optimal power flow is an effective way to simulate real and reactive power spot market. Both real and reactive power spot prices are expressed as a combination of different price components. It helps in spot price decomposition.

(iii) Inclusion of FACTS devices in the system reduces the spot prices. Cost of the FACTS devices can also be allocated to the reactive power loading condition in the system.

(iv) The marginal cost of reactive power is negligible compared to that of real power. However, wheeling rate of reactive power cannot be neglected.

CHAPTER 5

MATHEMATICAL FORMULATION FOR TCSC

Improvement of total transfer capacity was an important topic in the modern power system scenario. Heavily loaded circuits and buses with relatively low voltage, usually limit total transfer capability. It is well known that FACTS technology can control voltage magnitude, phase angle and circuit reactance, so it can redistribute the load flow and regulate bus voltage. FACTS devices were more effective for improving total transfer capability.

The total transfer capability of apparent power enhancement with FACTS can be calculated using optimal power flow formulation, which was given below.

$$\text{Max} \sum_{i \varepsilon T_L} Si \qquad (5.1)$$

Subject to

$$L\ (P,Q,V,\theta,Xk)=0 \qquad (5.2)$$

$$G\ (P.Q,V,\theta,Xk)=0 \qquad (5.3)$$

Where

T_L= Transmission lines

P = Vector of real power injections/extractions

Q=Vector of reactive power injections/extractions

V = Vector of voltage magnitudes

θ = Vector of voltage angles

Xk= FACTS control parameters

Equality constraint (5.2) corresponds to power flow equations for both real and reactive power. Inequality constraint (5.3) was the limits on the operating constraints such as real and reactive power flow limits of generation, transformer taps, line flow limits, bus voltage limits and limits on the FACTS control parameters.

5.1. SENSITIVITY CALCULATION

5.1.1 Total loss sensitivity indices

The loss in general refers to real power loss by reducing the line inductive reactance with capacitive reactance the power flow can be enhanced. The reason was the reduction in line reactance was reflected on the torque. Loss in general refers to real power loss in the form of heat; by reducing the line reactance the losses were reduced as a result the volt-ampere component closely matches the watt component. In short it can be said the network should operate closer to unity power factor. More over the transmission and distribution losses accounts to 21% in India. Hence the total real power loss sensitive (trpl) can be calculated as the change in total real power loss with compensation and the total real power loss without compensation to that of change in reactance without and with compensation.

$$\frac{\partial PL}{\partial X} = \frac{PLwi - PLwo}{Xwo - Xwi} \quad (5.4)$$

As per the above equation (5.4) it was clear that when there was negative answer it can be said as desired result and vice versa. This equation should be incorporated in the optimal power flow. For each degree of compensation a most negative value can be obtained and that corresponding line was said to be feasible solution. These negative values for each degree of series compensation from 1 to 30 degree was formed in an array and from that array the line corresponding to most negative value was chosen to be the optimal placement of the corresponding TCSC. This was found suitable from small to large test system. This process will be mobilized automatically in a network. The various

Indices calculation can be said as computationally feasible and conceptually reasonable approach and becomes mandatory in a deregulated environment.

5.1.2 Real power flow sensitivity indices

The total loss sensitivity refers loss with respect to the entire system whereas this real power flow refers to the individual real power flow in the lines. By placing the TCSC the line losses decreases, automatically the power flow enhances. This controllability of power flow in an electric power system without generation rescheduling or topological changes can improve the performance considerably. The real power flow can be calculated as the change of real power without compensation and with compensation to that of change in corresponding line reactance

$$ap = \frac{\partial p}{\partial X} = \frac{Pwo-Pwi}{Xwo-Xwi} \qquad (5.5)$$

The above equation (5.5) gives clear insight regarding the measure of real power index of a network. If negative value was obtained at the end of OPF analysis then it was referred as the desired result. This feasibility shows in both functionality and economics.

5.1.3 Reactive power flow sensitivity indices

Only real power can be transmitted to long distances and the reactive power to short distances. To maximize the reactive power flow and to raise the power factor in a transmission line the VAR loss should be minimum. On the other hand the VAR component should not be nullified since almost all the loads are inductive in nature its presence becomes significant. Parallel lines of unequal ratings or impedances induce uneven loadings of the network transfer paths. Hence reactive power flow sensitivity index calculation becomes significant. The reactive power flow can be calculated as the change of reactive power without compensation and with compensation to that of change in corresponding line reactance.

$$bq = \frac{\partial Q}{\partial X} = \frac{Qwo\text{-}Qwi}{Xwo\text{-}Xwi} \qquad (5.6)$$

The above equation (5.6) gives clear insight regarding the measure of reactive power index of a network. If negative value was obtained at the end of OPF analysis then it was referred as the desired result.

5.1.4 PI Sensitivity

It should be calculated for static considerations based on the reduction in the power flow performance index (PI). The sensitivity of the system loading under normal and contingency cases as given below

$$PI = \sum_{m=1}^{n} \frac{W}{2n}\left(\frac{S}{S^{max}}\right)^{2n} \qquad (5.7)$$

Where

S = the apparent power flow

S^{max} = the maximum line limit

n = the exponent

W= a real non negative weighting coefficient which may use to reflect the importance of lines.

PI as per equation (5.7) will be small when all the lines are within their limits and reach a high value when there were overloads. Thus it provides a good measure of severity of the line overloads for a given state of the power system. Reduction in PI shows that reduction in overloading of transmission line for high value of exponent.

Is S was more than S^{max} then particular line was said to be congested and preventive measures had to be taken by applying the FACTS controller TCSC in the congested line and varying the degree of series compensation gradually, congestion relief can be obtained. Hence the integration of FACTS models in an existing power system optimization package leads to the flexibility and modularity for allowing the easy formulation of the modeling equations.

5.1.5 Flowchart for TCSC

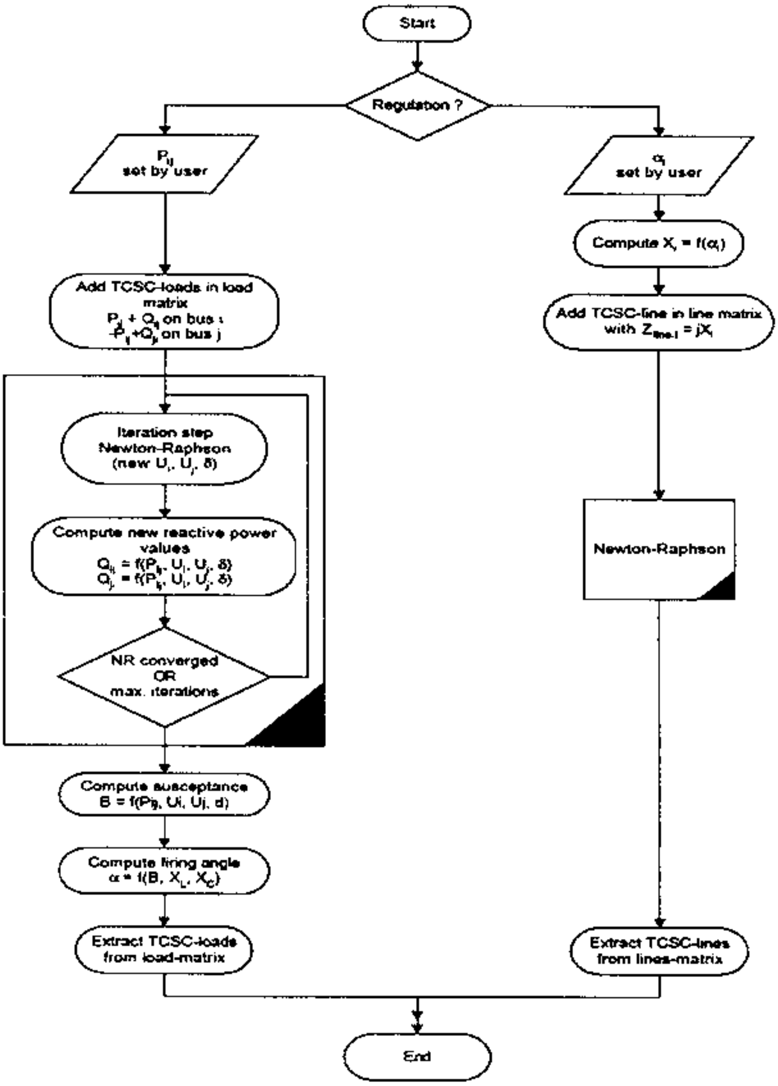


Figure 5.1 Flowchart

5.2. 14 Bus system

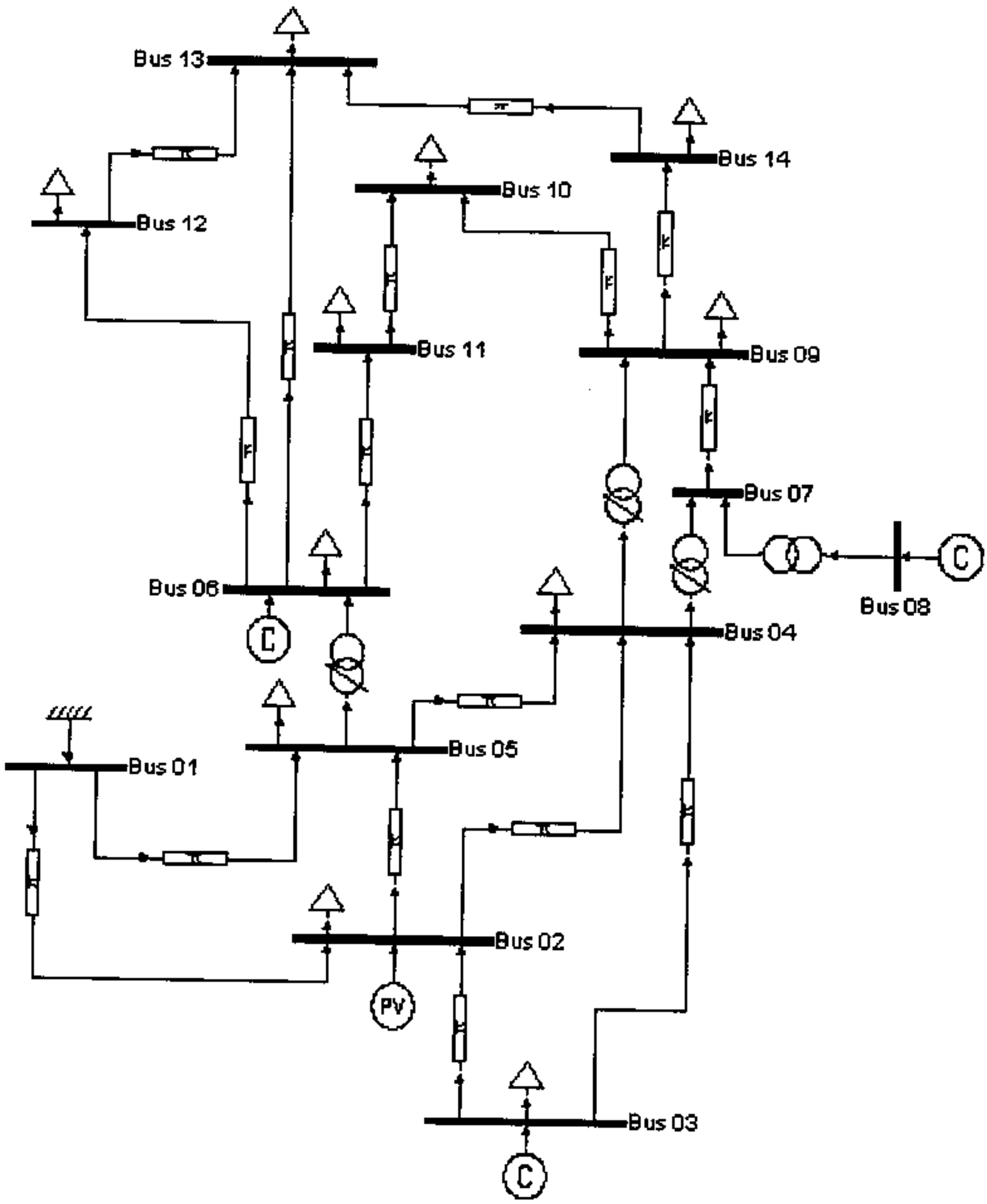


Figure 5.2 14-Bus systems

The actual power system consists of a large number of generators, buses and transmission lines. In order to analyse the power system with respect to its dynamic performance, a simplified 14-bus network model was established, as shown in Figure 5.2

CHAPTER 6

SIMULATION RESULTS

A MATLAB coding has been developed to optimize the power flow to reduce the error, after incorporating the FACTS Devices in 14 bus system. Voltage profile at the buses has improved and the real and reactive power transfer is controlled and the power flow control ranges for these device in the 14 bus system are drawn. Coordination of power flow control performance for TCSC, before and after optimization of power flow is shown. The MATLAB Codings generated are listed in APPENDIX 2.

6.1. TCSC IN TRANSMISSION LINE

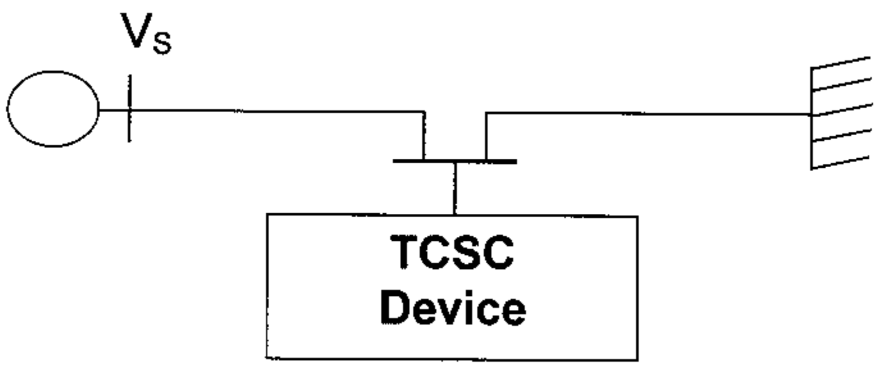


Figure 6.1 TCSC in transmission line

TCSC is installed on the branch that represents a real transmission line. TCSC will be connected at the sending end of the transmission line with capacitive part equal to zero.(XFixC=0). The impedance of the installed TCSC's is fixed to zero by activating the following constraints:

XiTCSC = 0

6.2 TCSC IN TRANSMISSION LINE DURING FAULT (LINE TO GROUND)

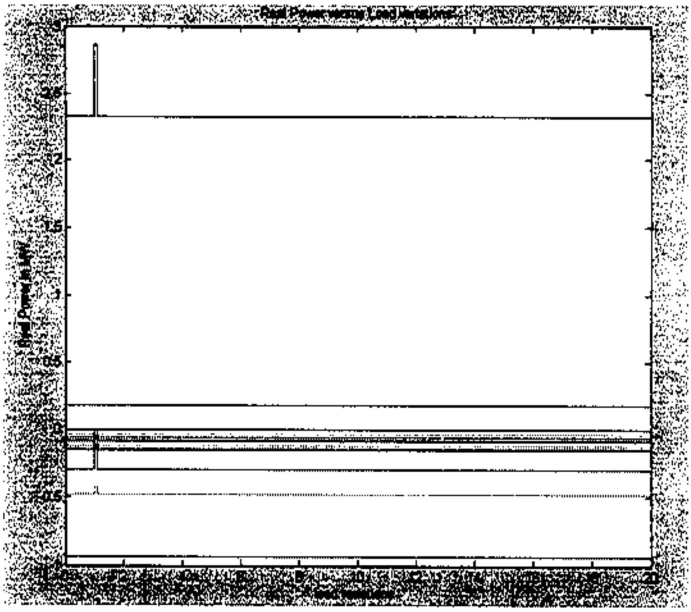


Figure 6.2 Real power Vs Load variations

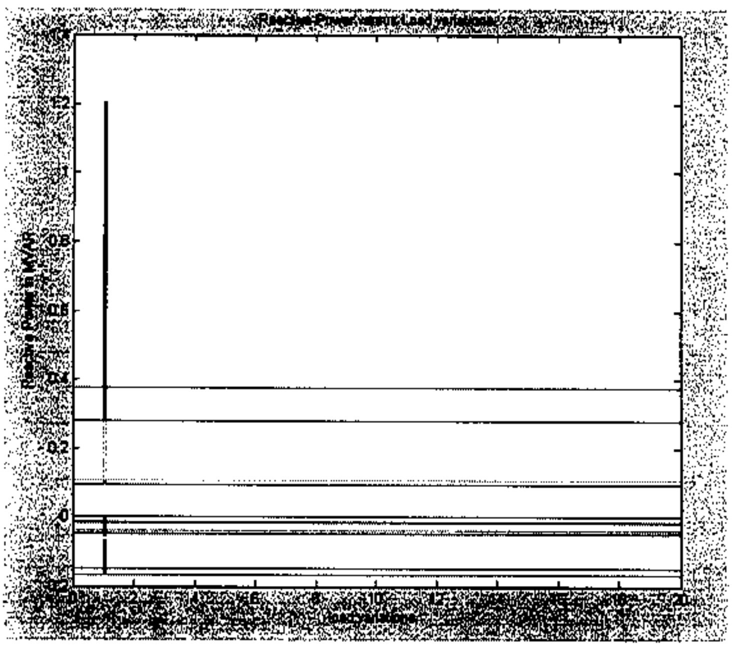


Figure 6.3 Reactive power Vs Load variations

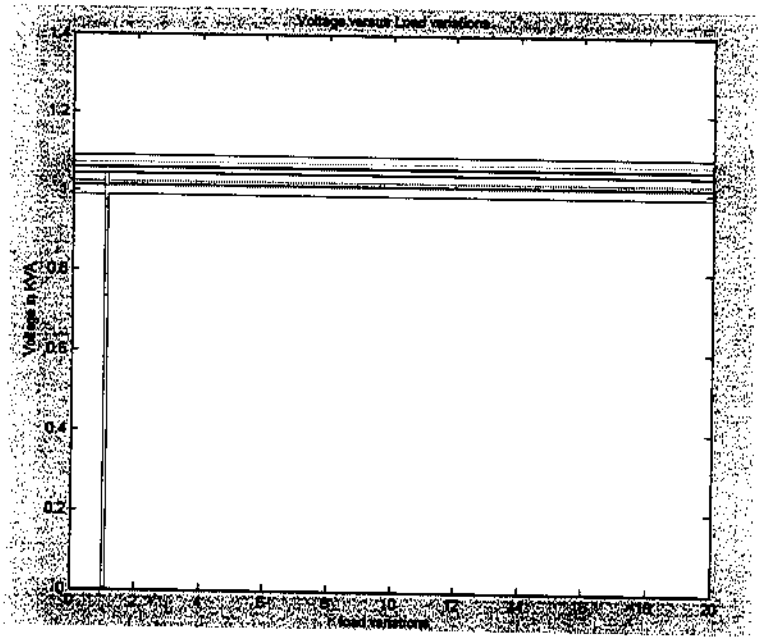


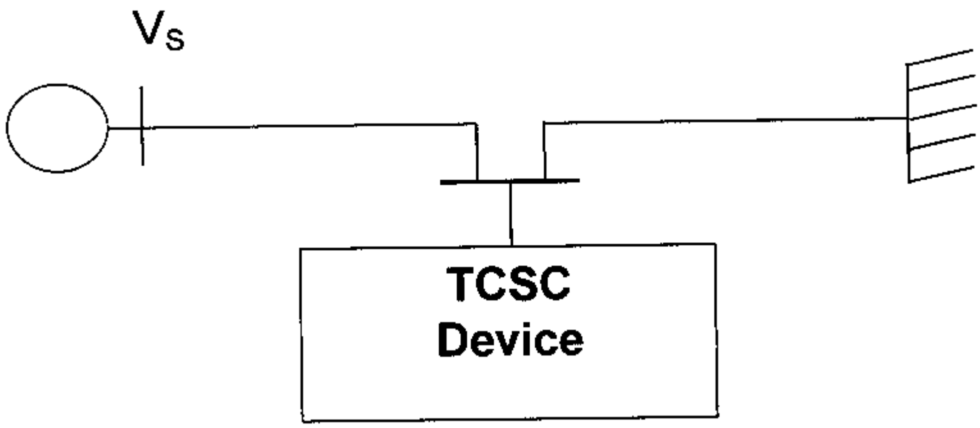
Figure 6.4 Voltage Vs Load variations

Simulated result for TCSC is shown here. TCSC is incorporated in transmission line and the power flow control ranges are found. A graph for real power, reactive power and voltage was shown.

1	1.060	0.000	2.327	-0.047
2	1.045	-0.087	0.183	0.375
3	1.010	-0.223	-0.942	0.093
4	1.010	-0.179	-0.478	-0.040
5	1.015	-0.152	-0.076	-0.016
6	1.070	-0.245	-0.112	0.104
7	1.045	-0.236	0.000	0.000
8	1.090	-0.236	0.000	0.279
9	1.024	-0.266	-0.295	-0.166
10	1.024	-0.267	-0.090	-0.058
11	1.043	-0.258	-0.035	-0.018
12	1.057	-0.257	-0.061	-0.016
13	1.055	-0.257	-0.135	-0.058
14	1.991	-0.299	-0.149	-0.050

Table 6.1 TCSC in Transmission line during fault

6.3. TCSC IN TRANSMISSION LINE AFTER FAULT CLEARANCE



The fault will be cleared by placing the TCSC in optimal location. Hence the real power, reactive power and voltage stability will be improved.

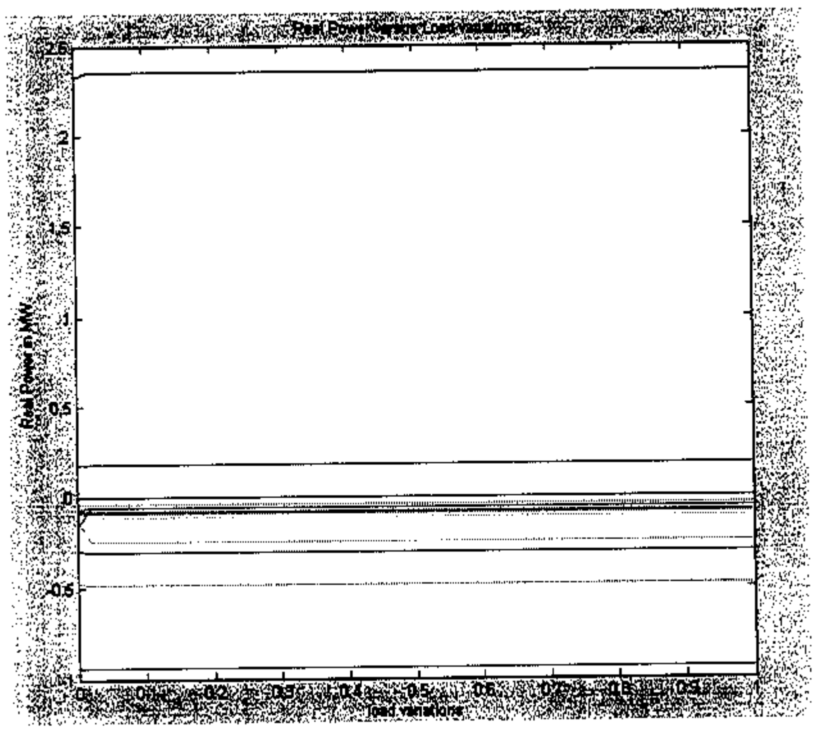


Figure 6.5 Real power Vs Load variations

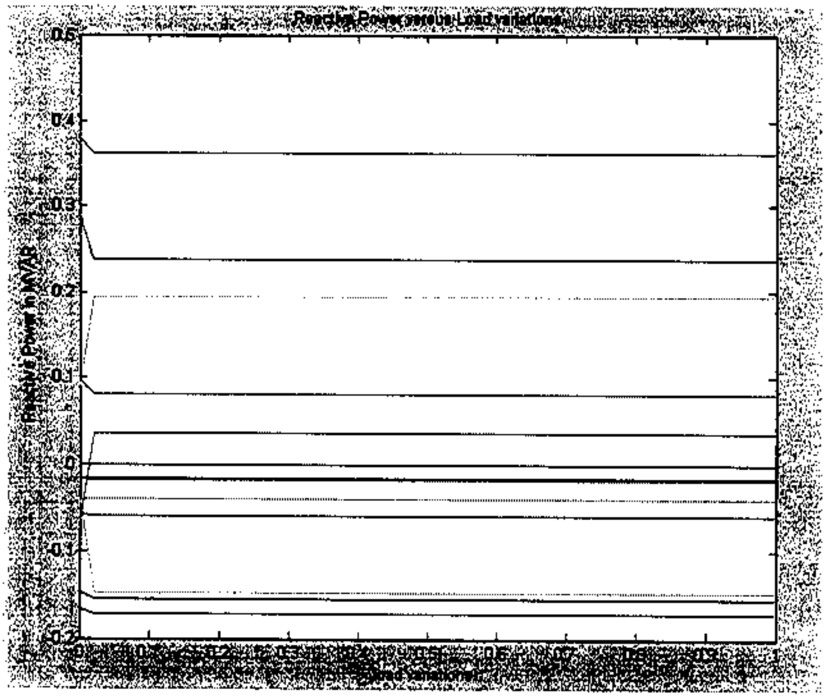


Figure 6.6 Reactive power Vs Load variations

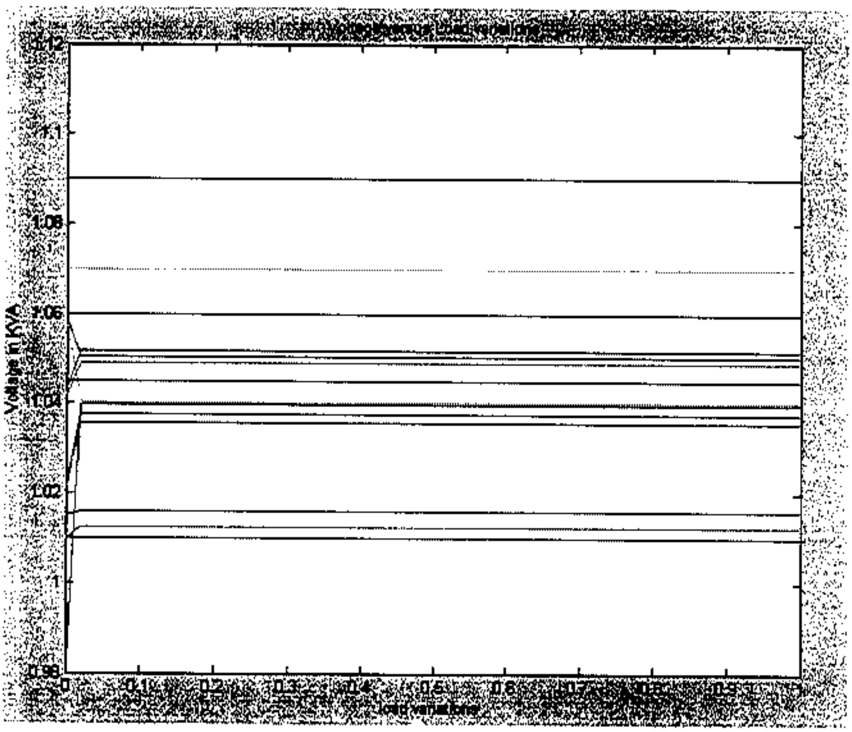


Figure 6.7 Voltage Vs Load variations

Simulated result of TCSC in the transmission line after the fault clearance is found. A graph for real power, reactive power and voltage stability are improved.

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
1	1.060	0.000	2.356	-0.155
2	1.045	-0.088	0.183	0.362
3	1.010	-0.224	-0.942	0.081
4	1.012	-0.181	-0.480	-0.040
5	1.016	-0.155	-0.076	-0.016
6	1.070	-0.260	-0.112	0.195
7	1.052	-0.233	0.000	0.000
8	1.090	-0.233	0.000	0.237
9	1.038	-0.260	-0.304	-0.171
10	1.036	-0.265	-0.092	-0.060
11	1.049	-0.265	-0.035	-0.018
12	1.050	-0.276	-0.060	-0.016
13	1.040	-0.277	-0.242	-0.048
14	1.040	-0.278	-0.056	-0.035

Table 6.2 TCSC in Transmission line after the fault clearance

CHAPTER 7

HARDWARE IMPLEMENTATION

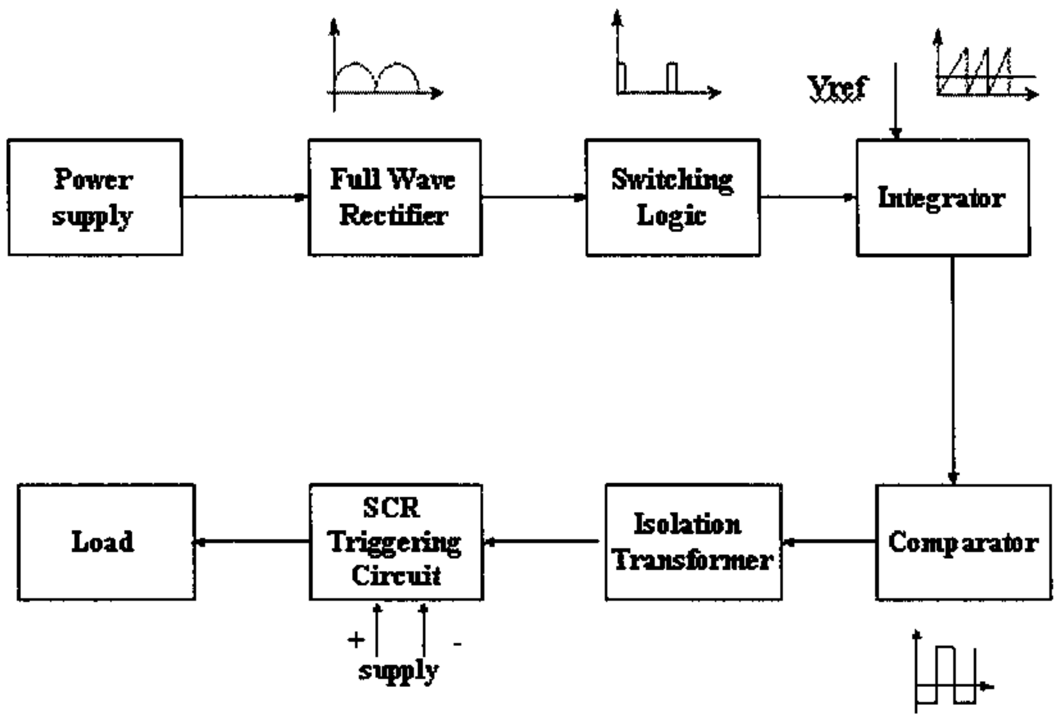


Figure 7.1 Block diagram

7.1. TECHNICAL DESCRIPTION

The hardware design consists of following components

7.1.1 Power supply unit

The power supply unit provides the necessary power supply for the whole circuit. It gives a regulated power supply of +5V and ±12V for running the processor and driving the relay.

There is a step down transformer which is a two tapped one of which one provides 230/9 – 0 V and the other tapping provides 230/ 15 – 0 – 15 V. The 9 -0 V provides the power supply for the micro controller and the other 15 – 0 -15 V provides power supply for the 7th and 4th Pin of the OP-AMP LM741. The power supply unit consists of the following IC's viz... 7805, 7812 and 7912 for voltage regulation

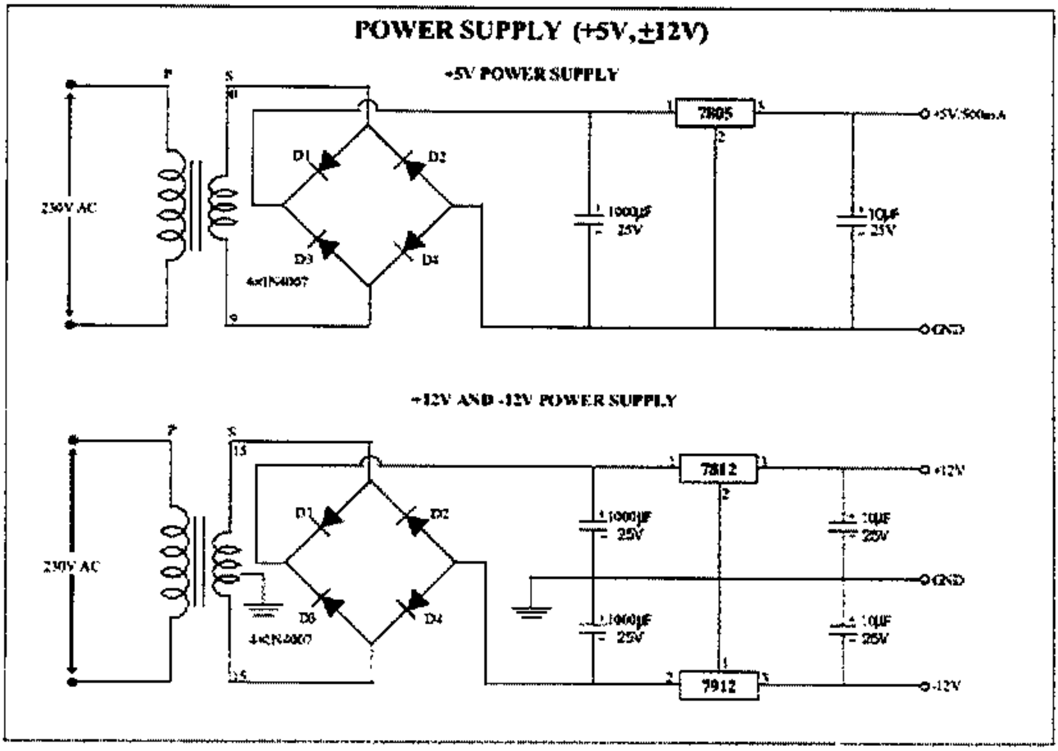


Figure 7.2 Power supply unit

7.1.2 Full wave rectifier

30V AC sine wave output from transformer secondary is connected to a diode full wave rectified (center tap) which generates full wave rectified output.

7.1.3 Zero crossing detector

Zero crossing detector is a transistor circuit, which detects the zero crossings of input waveform and generates a square wave.

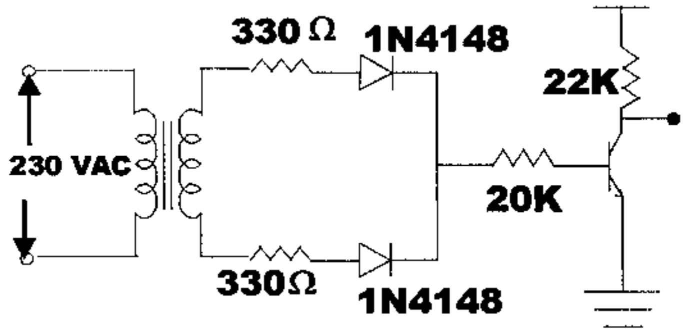


Figure 7.3 Rectifier and Zero crossing detector

7.1.4 Integrator

The square wave output from the zero crossing detector is fed as input to an op-AMP integrator circuit. It generates a ramp waveform.

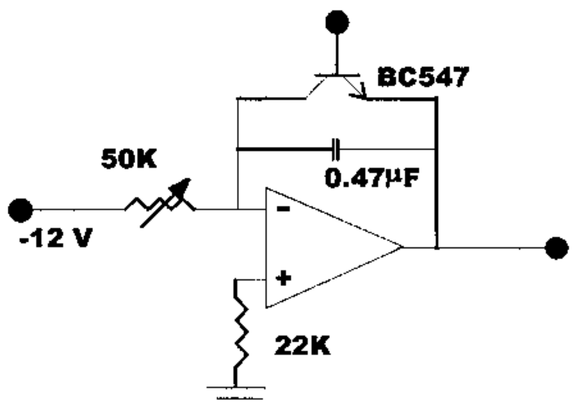


Figure 7.4 Integrator

7.1.5 Comparator

An op-amp comparator compares the reference ramp waveform at inverting input with a variable DC input and generates rectangular pulses at the output. By varying the potentiometer knob connected to this section, the width of output pulses can be varied.

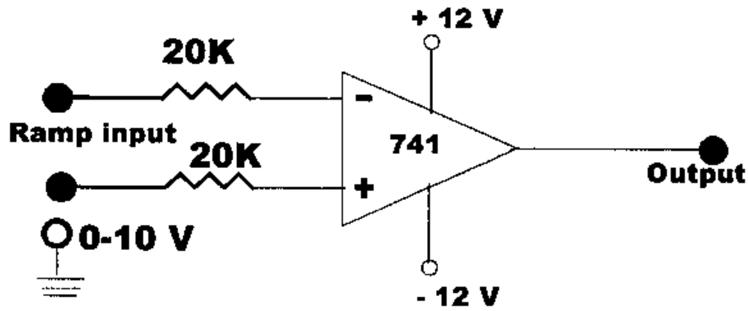


Figure 7.5 Comparator

7.1.6 Astable multivibrator

This circuit is designed using 555 IC, which generates square waves of 5 KHz frequency.

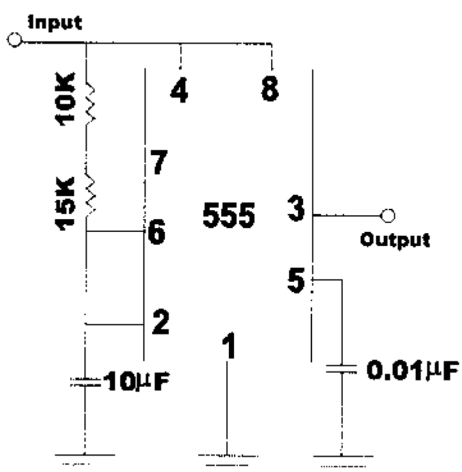


Figure 7.6 Astable multivibrator

7.1.7 Logic gate

A 2 input NAND gate is used with one input connected to comparator output and the other input fed from astable multivibrator output, through resistors. The output of the NAND gate is shown in the waveform

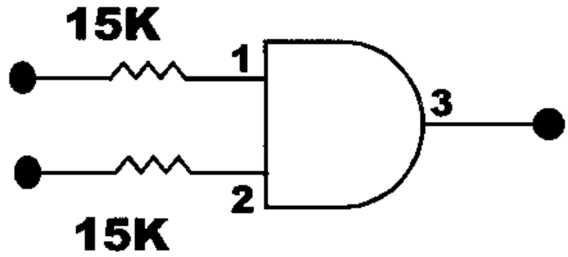


Figure 7.7 NAND gate

7.1.8 Isolation

The logic gate output is connected to the isolation section through a transistor switching circuit. When pulses from gate output are fed to this circuit, the output transistor will conduct through the pulse transformer primary inducing a pulse in the primary and secondary of the transformer. The driver circuit also increases the amplitude of trigger pulses up to the required value. This section provides isolation between low voltage and high voltage sections. It generates two sets of trigger pulses to fire each SCR in the power circuit.

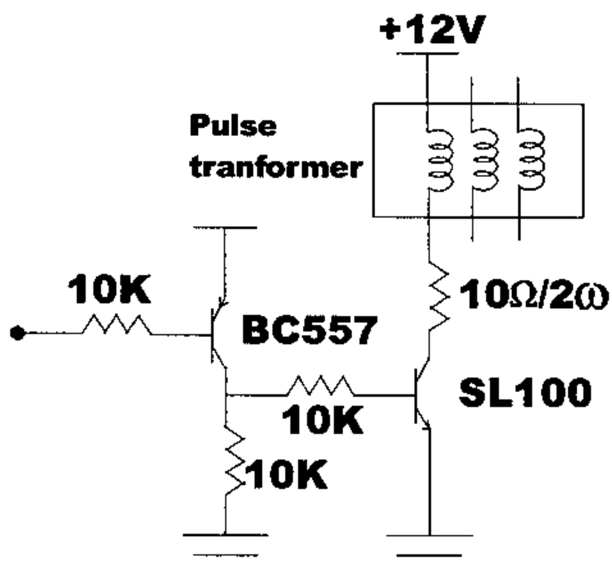


Figure 7.8 Switching & Isolation circuit

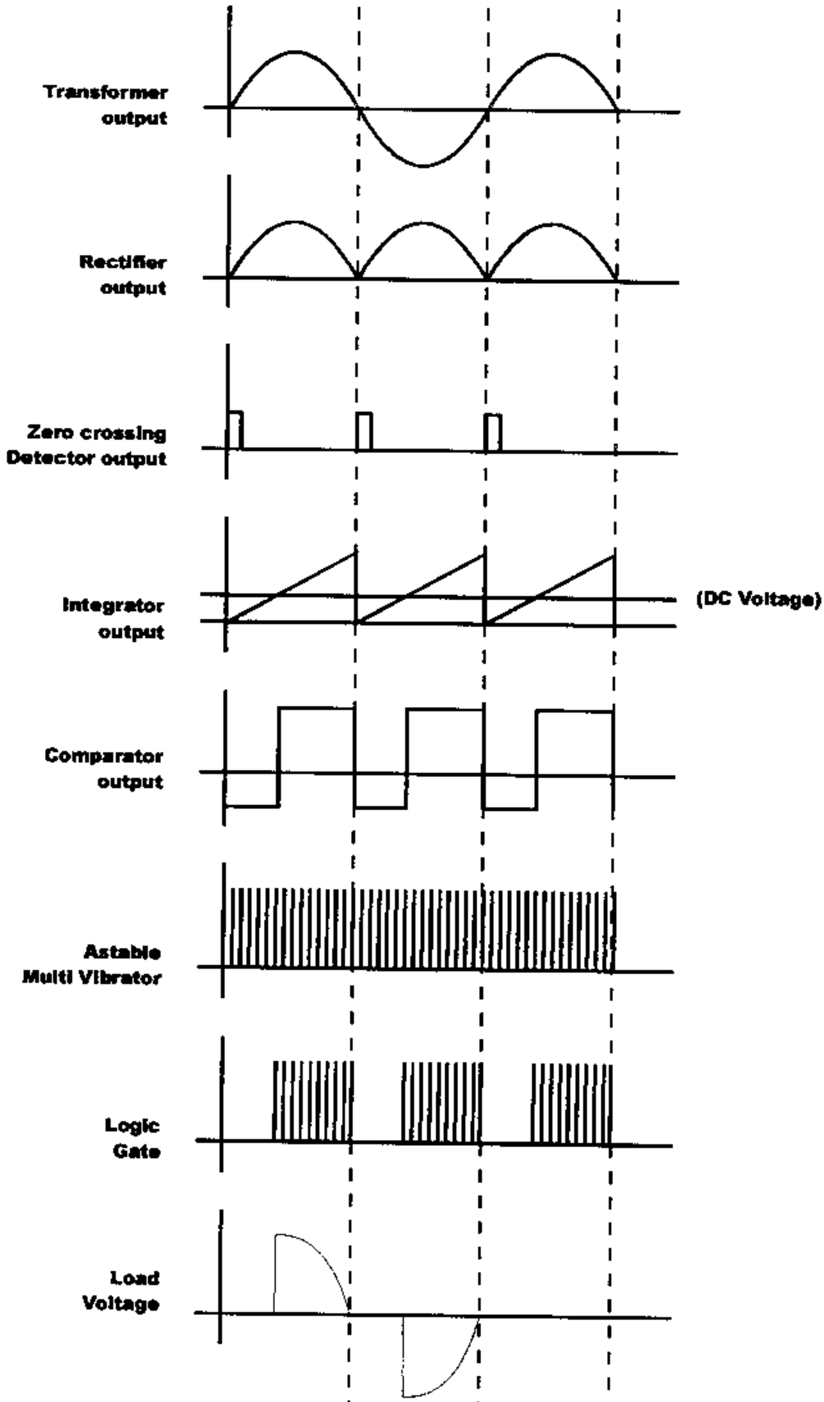


Figure 7.9 Control section waveform

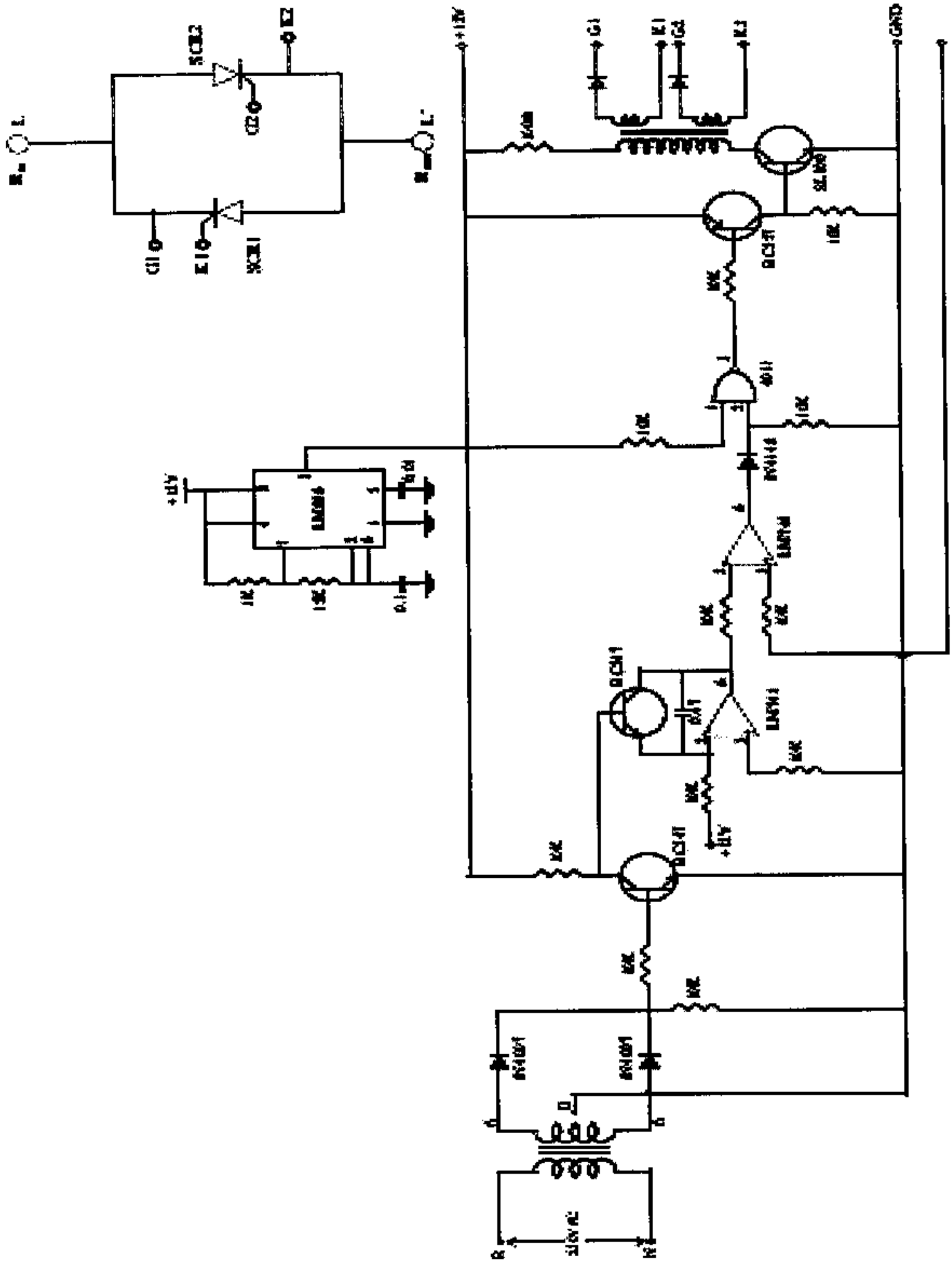


Figure 7.10 Circuit diagram

CHAPTER 8

CONCLUSION

The power flow can be rapidly and flexibly controlled by FACTS devices. In this project, based on the steady state models of FACTS, power flow controllability with single FACTS device is analytically investigated. When there are several such devices in the system, coordination of power flow control performances of these devices can be defined as an optimization problem. A TCSC power flow model was implemented in 14 bus system which includes Newton-Raphson load flow algorithm. Optimal placement of these devices leads to improved congestion reduction and less curtailment in the desired power transactions. By placing TCSC in optimal location, so that real power, reactive power and voltage stability will be improved. Time damping of the power system oscillation can be reduced through effective changes in line impedance. Through TCSC the effective line impedance can be controlled within a few milliseconds.

APPENDIX 1

Bus.con = [...

Bus no	Voltage KV	Volt / unit	Phase angle	Area	Region
1	69	1	0	4	1;
2	69	1	0	4	1;
3	69	1	0	4	1;
4	69	1	0	4	1;
5	69	1	0	4	1;
6	13.8	1	0	2	1;
7	13.8	1	0	2	1;
8	18	1	0	3	1;
9	13.8	1	0	2	1;
10	13.8	1	0	2	1;
11	13.8	1	0	2	1;
12	13.8	1	0	2	1;
13	13.8	1	0	2	1;
14	13.8	1	0	2	1];

Line.con = [...

Bus no.		Power MVA	Voltage KV	Frequency	Resistance (pu)	Reactance (pu)	Susceptance (pu)
2	5	100	69	60	0.05695	0.17388	0.034
6	12	100	13.8	60	0.12291	0.25581	0
12	13	100	13.8	60	0.22092	0.19988	0
6	13	100	13.8	60	0.06615	0.13027	0
6	11	100	13.8	60	0.09498	0.1989	0
11	10	100	13.8	60	0.08205	0.19207	0
9	10	100	13.8	60	0.03181	0.0845	0
9	14	100	13.8	60	0.12711	0.27038	0
7	9	100	13.8	60	0	0.11001	0
1	2	100	69	60	0.01938	0.05917	0.0528
3	2	100	69	60	0.04699	0.19797	0.0438
3	4	100	69	60	0.06701	0.17103	0.0346
1	5	100	69	60	0.05403	0.22304	0.0492
5	4	100	69	60	0.01335	0.04211	0.0128
2	4	100	69	60	0.05811	0.17632	0.0374
5	6	100	69	60	0.25202	0	0.932
4	9	100	69	60	0.55618	0	0.969
4	7	100	69	60	0.20912	0	0.978
8	7	100	18	60	1.30435	0.17615	0

];

SW.con = [...

Bus no.	Power MVA	Voltage KV	Voltage mag/unit	Phase Angle	Qmax	Qmin	Vmax	Vmin	Pactive	Loss co-eff
1	100	69	1.06	0	9.9	-9.9	1.2	0.8	2.324	1];

PV.con = [...

Bus no.	Power MVA	Voltage KV	Actual power	Voltage mag/unit	Qmax	Qmin	Vmax	Vmin	Loss
2	100	69	0.4	1.045	0.5	-0.4	1.2	0.8	1;
6	100	13.8	0	1.07	0.24	-0.06	1.2	0.8	1;
3	100	69	0	1.01	0.4	0	1.2	0.8	1;
8	100	18	0	1.09	0.24	-0.06	1.2	0.8	1];

PQ.con = [...

Bus no.	Power MVA	Voltage KV	Pactive (pu)	Preactive (pu)	Max Voltage	Min Voltage	
11	100	13.8	0.035	0.018	1.2	0.8	
13	100	13.8	0.135	0.058	1.2	0.8	
3	100	69	0.942	0.19	1.2	0.8	
5	100	69	0.076	0.016	1.2	0.8	
2	100	69	0.217	0.127	1.2	0.8	
6	100	13.8	0.112	0.075	1.2	0.8	
4	100	69	0.478	0.04	1.2	0.8	
14	100	13.8	0.149	0.05	1.2	0.8	
12	100	13.8	0.061	0.016	1.2	0.8	
10	100	13.8	0.09	0.058	1.2	0.8	
9	100	13.8	0.295	0.166	1.2	0.8	];

Supply.con = [...
1 100 0.8 1 0 32 0];

Fault.con = [...

Bus no	Power MVA	Voltage	frequency	Fault Time	Fault Resistance
14	100	13.8	60	1	0.001];

Tcsc con = [..

Bus no		Power	Voltage	Frequency	Gain	XL	XC
14	13	100	13.8	60	10	0.02	0.01

Varname.bus = {...
'Bus 01'; 'Bus 02'; 'Bus 03'; 'Bus 04'; 'Bus 05';
'Bus 06'; 'Bus 07'; 'Bus 08'; 'Bus 09'; 'Bus 10';
'Bus 11'; 'Bus 12'; 'Bus 13'; 'Bus 14'};

APPENDIX 2-Power flow solution

```
%power flow solution by newton traphson method
%load the figure data
clc;
clear all;
close all;
load maindata;

Path.data=cd;
Path.local=cd;

%define the global data
global maindata;

%run the main window
fm_main

%pause the procedure
pause;

%output of the file

Po=Varout.p(end,:);
Qo=Varout.q(end,:);
Vo=Varout.V(end,:);
angt=Varout.ang(end,:);


%ploting the Variable
figure,plot(Varout.t,Varout.p);
title('Real Power versus Load variations');
xlabel('load variations ');
ylabel('Real Power in MW');


%ploting the Variable
figure,plot(Varout.t,Varout.q);
title('Reactive Power versus Load variations');
xlabel('load variations ');
ylabel('Reactive Power in MVAR');

%ploting the Variable
figure,plot(Varout.t,Varout.V);
title('Voltage versus Load variations');
xlabel('load variations ');
```

```
ylabel('Voltage in KVA');


%displaying Variable

%clc
disp('   Bus  Voltage  Angle      Real power      reacive power');
disp(  '   No.  Mag.    Degree       MW             Mvar  ' );

for n=1:14
    fprintf(' %5g', n), fprintf(' %7.3f', Vo(n)),fprintf(' %8.3f', angt(n))
    fprintf('      %8.3f', Po(n)), fprintf('     %9.3f \n', Qo(n)),
end
```

APPENDIX 3-TCSC Codings

```
function  fm_tcsc(flag)
% FM_TCSC defines Synchronous Machines
%

global Tcsc Bus DAE Settings

type = Tcsc.con(:,6);
ty1 = find(type == 1);
ty2 = find(type == 2);
V1 = DAE.V(Tcsc.bus1);
V2 = DAE.V(Tcsc.bus2);
t1 = DAE.a(Tcsc.bus1);
t2 = DAE.a(Tcsc.bus2);
ss = sin(t1-t2);
cc = cos(t1-t2);
Pref = Tcsc.con(:,8);

if Settings.init
  Kr = Tcsc.con(:,7);
  Tw = Tcsc.con(:,13);
  T1 = Tcsc.con(:,14);
  T2 = Tcsc.con(:,15);
  T3 = Tcsc.con(:,16);
  x_max = Tcsc.con(:,9);
  x_min = Tcsc.con(:,10);
end

switch flag
 case 0
 Tcsc.B = Pref./V1./V2./ss;
 SI = zeros(Tcsc.n,1);
 if ty1
    SI(ty1) = -1./Tcsc.B(ty1);
    jdx = find(SI(ty1) > x_max(ty1));
    if jdx
    tcscwarn(ty1(jdx),' Xc is over its maximum limit.')
    end
    jdx = find((SI(ty1)) < x_min(ty1));
    if jdx
     tcscwarn(ty1(jdx),' Xc is under its minimum limit.')
  end
  end
  if ty2
  xC = Tcsc.con(ty2,12);
```

```
xL = Tcsc.con(ty2,11);
% initialization of alpha
ar = -pi:0.001:pi;
for i = 1:length(ty2)
% find a "good" initial guess in a brutal way...
B = tcsca(ar,xC(i),xL(i));
[val,idx] = min(abs(B-Tcsc.B(ty2(i))));
  a = ar(idx);
  err = 1;
  iter = 0;
  while abs(err) > Settings.lftol
      if iter > 20, break, end
      err = (tcsca(a,xC(i),xL(i)) - Tcsc.B(ty2(i)))/tcscda(a,xC(i),xL(i));
      a = a + err;
      iter = iter + 1;
  end
  if iter > 20
  tcscwarn(ty2(i),[' convergence not reached when initializing' ...
                    ' the firing angle alpha.'])
  end
  SI(ty2(i)) = a;
  end
  jdx = find(SI(ty2) > x_max(ty2));
  if jdx
  tcscwarn(ty2(jdx),' alpha is over its maximum limit.')
  end
  jdx = find(SI(ty2) < x_min(ty2));
  if jdx
  tcscwarn(ty2(jdx),' alpha is under its minimum limit.')
 end
 %Tcsc.con(ty2,7) = -Tcsc.con(ty2,7);
end
DAE.x(Tcsc.x1) = SI;
DAE.x(Tcsc.x2) = SI;
DAE.x(Tcsc.x3) = SI.*(1-Tcsc.con(:,15)./Tcsc.con(:,16));
Tcsc.con(:,8) = Pref - DAE.x(Tcsc.x1)./Tcsc.con(:,7)./Tcsc.con(:,13);

case 1 % algebraic equations

 if Settings.init % complete model
  Tcsc.Pe = V1.*V2.*ss.*Tcsc.B;
  DAE.gp = DAE.gp + sparse(Tcsc.bus1,1, Tcsc.Pe,Bus.n,1);
  DAE.gq = DAE.gq + sparse(Tcsc.bus1,1, V1.*(V1-V2.*cc).*Tcsc.B,Bus.n,1);
  DAE.gp = DAE.gp + sparse(Tcsc.bus2,1,-Tcsc.Pe,Bus.n,1);
  DAE.gq = DAE.gq + sparse(Tcsc.bus2,1, V2.*(V2-V1.*cc).*Tcsc.B,Bus.n,1);
 else % static model used for power flow solution
```

```
  DAE.gp = DAE.gp + sparse(Tcsc.bus1,1, Pref,Bus.n,1);
  DAE.gq = DAE.gq + sparse(Tcsc.bus1,1, Pref.*(V1./V2./ss-cc./ss),Bus.n,1);
  DAE.gp = DAE.gp + sparse(Tcsc.bus2,1,-Pref,Bus.n,1);
  DAE.gq = DAE.gq + sparse(Tcsc.bus2,1, Pref.*(V2./V1./ss-cc./ss),Bus.n,1);
 end

case 2 % algebraic Jacobians

 if Settings.init  % complete model
  a1 = ss.*Tcsc.B;
  a2 = cc.*Tcsc.B;
  a3 = V1.*V2;
  a4 = a3.*a1;
  a5 = a3.*a2;
  % dP1/dy
  DAE.J12 = DAE.J12 + sparse(Tcsc.bus1,Tcsc.bus1, V2.*a1,Bus.n,Bus.n);
  DAE.J12 = DAE.J12 + sparse(Tcsc.bus1,Tcsc.bus2, V1.*a1,Bus.n,Bus.n);
  DAE.J11 = DAE.J11 + sparse(Tcsc.bus1,Tcsc.bus1, a5,Bus.n,Bus.n);
  DAE.J11 = DAE.J11 + sparse(Tcsc.bus1,Tcsc.bus2,-a5,Bus.n,Bus.n);
  % dP2/dy
  DAE.J22 = DAE.J22 + sparse(Tcsc.bus1,Tcsc.bus1,(2*V1-
V2.*cc).*Tcsc.B,Bus.n,Bus.n);
  DAE.J22 = DAE.J22 + sparse(Tcsc.bus1,Tcsc.bus2,-V1.*a2,Bus.n,Bus.n);
  DAE.J21 = DAE.J21 + sparse(Tcsc.bus1,Tcsc.bus1, a4,Bus.n,Bus.n);
  DAE.J21 = DAE.J21 + sparse(Tcsc.bus1,Tcsc.bus2,-a4,Bus.n,Bus.n);
  % dQ1/dy
  DAE.J12 = DAE.J12 + sparse(Tcsc.bus2,Tcsc.bus1,-V2.*a1,Bus.n,Bus.n);
  DAE.J12 = DAE.J12 + sparse(Tcsc.bus2,Tcsc.bus2,-V1.*a1,Bus.n,Bus.n);
  DAE.J11 = DAE.J11 + sparse(Tcsc.bus2,Tcsc.bus1,-a5,Bus.n,Bus.n);
  DAE.J11 = DAE.J11 + sparse(Tcsc.bus2,Tcsc.bus2, a5,Bus.n,Bus.n);
  % dQ2/dy
  DAE.J22 = DAE.J22 + sparse(Tcsc.bus2,Tcsc.bus2,(2*V2-
V1.*cc).*Tcsc.B,Bus.n,Bus.n);
  DAE.J22 = DAE.J22 + sparse(Tcsc.bus2,Tcsc.bus1,-V2.*a2,Bus.n,Bus.n);
  DAE.J21 = DAE.J21 + sparse(Tcsc.bus2,Tcsc.bus1, a4,Bus.n,Bus.n);
  DAE.J21 = DAE.J21 + sparse(Tcsc.bus2,Tcsc.bus2,-a4,Bus.n,Bus.n);
 else %static model used for power flow solution
  ct = cot(t1-t2);
  % dQ1/dy
  DAE.J22 = DAE.J22 + sparse(Tcsc.bus1,Tcsc.bus1, Pref./V2./ss,Bus.n,Bus.n);
  DAE.J22 = DAE.J22 + sparse(Tcsc.bus1,Tcsc.bus2,-
V1.*Pref./V2./V2./ss,Bus.n,Bus.n);
  DAE.J21 = DAE.J21 + sparse(Tcsc.bus1,Tcsc.bus1, Pref.*(1+ct.*ct-
V1.*ct./ss./V2),Bus.n,Bus.n);
  DAE.J21 = DAE.J21 + sparse(Tcsc.bus1,Tcsc.bus2,-Pref.*(1+ct.*ct-
V1.*ct./ss./V2),Bus.n,Bus.n);
```

```
 % dQ2/dy
 DAE.J22 = DAE.J22 + sparse(Tcsc.bus2,Tcsc.bus2, Pref./V1./ss,Bus.n,Bus.n);
 DAE.J22 = DAE.J22 + sparse(Tcsc.bus2,Tcsc.bus1,-
V2.*Pref./V1./V1./ss,Bus.n,Bus.n);
 DAE.J21 = DAE.J21 + sparse(Tcsc.bus2,Tcsc.bus1, Pref.*(1+ct.*ct-
V2.*ct./ss./V1),Bus.n,Bus.n);
 DAE.J21 = DAE.J21 + sparse(Tcsc.bus2,Tcsc.bus2,-Pref.*(1+ct.*ct-
V2.*ct./ss./V1),Bus.n,Bus.n);
 end

 case 3 % differential equations

  if Settings.init
   DAE.f(Tcsc.x1) = -Kr.*(Pref-Tcsc.Pe) - DAE.x(Tcsc.x1)./Tw;
   DAE.f(Tcsc.x2) = (DAE.x(Tcsc.x1)-DAE.x(Tcsc.x2))./T1;
   DAE.f(Tcsc.x3) = ((1-T2./T3).*DAE.x(Tcsc.x1)-DAE.x(Tcsc.x3))./T3;
   SI = max(DAE.x(Tcsc.x3) + DAE.x(Tcsc.x2).*T2./T3,x_min);
   SI = min(SI,x_max);
   % compute susceptances Tcsc.B
   if ~isempty(ty1), Tcsc.B(ty1) = -1./SI(ty1); end
   if ~isempty(ty2), Tcsc.B(ty2) = -tcsca(SI(ty2),Tcsc.con(ty2,12),Tcsc.con(ty2,11)); end
 end

 case 4 % state Jacobians

  if Settings.init
   DB = zeros(Tcsc.n,1);
   SI = DAE.x(Tcsc.x3) + DAE.x(Tcsc.x2).*T2./T3;
   if ~isempty(ty1)
   DB(ty1) = 1./SI(ty1)./SI(ty1);
   end
   if ~isempty(ty2)
   DB(ty2) = tcscda(SI(ty2),Tcsc.con(ty2,12),Tcsc.con(ty2,11));
   end

   DAE.Fx = DAE.Fx + sparse(Tcsc.x1,Tcsc.x1,-1./Tw,DAE.n,DAE.n);
   DAE.Fx = DAE.Fx + sparse(Tcsc.x2,Tcsc.x1, 1./T1,DAE.n,DAE.n);
   DAE.Fx = DAE.Fx + sparse(Tcsc.x2,Tcsc.x2,-1./T1,DAE.n,DAE.n);
   DAE.Fx = DAE.Fx + sparse(Tcsc.x3,Tcsc.x2,-(1-T2./T3)./T3,DAE.n,DAE.n);
   DAE.Fx = DAE.Fx + sparse(Tcsc.x3,Tcsc.x3,-1./T3,DAE.n,DAE.n);

  a0 = V1.*V2;
  a1 = a0.*ss;
  a2 = V1-V2.*cc;
  a3 = -Kr.*ss.*Tcsc.B;
  a4 = -a0.*Kr.*cc.*Tcsc.B;
```

```
  DAE.Fy = DAE.Fy + sparse(Tcsc.x1,Bus.n+Tcsc.bus2,V1.*a3,DAE.n,2*Bus.n);
  DAE.Fy = DAE.Fy + sparse(Tcsc.x1,Tcsc.bus1, a4,DAE.n,2*Bus.n);
  DAE.Fy = DAE.Fy + sparse(Tcsc.x1,Tcsc.bus2,-a4,DAE.n,2*Bus.n);

  % windup limiter
  a = find(SI < x_max & SI > x_min);

  if ~isempty(a)

    DAE.Fx = DAE.Fx +
sparse(Tcsc.x1(a),Tcsc.x3(a),Kr(a).*a1(a).*DB(a),DAE.n,DAE.n);
    DAE.Fx = DAE.Fx +
sparse(Tcsc.x1(a),Tcsc.x2(a),Kr(a).*a1(a).*DB(a).*T2(a)./T3(a),DAE.n,DAE.n);

    DAE.Gx = DAE.Gx + sparse(Tcsc.bus1(a),Tcsc.x3(a),a1(a).*DB(a),2*Bus.n,DAE.n);
    DAE.Gx = DAE.Gx +
sparse(Bus.n+Tcsc.bus1(a),Tcsc.x3(a),V1(a).*a2(a).*DB(a),2*Bus.n,DAE.n);
    DAE.Gx = DAE.Gx + sparse(Tcsc.bus2(a),Tcsc.x3(a),-
a1(a).*DB(a),2*Bus.n,DAE.n);
    DAE.Gx = DAE.Gx +
sparse(Bus.n+Tcsc.bus2(a),Tcsc.x3(a),V2(a).*a2(a).*DB(a),2*Bus.n,DAE.n);

    DAE.Gx = DAE.Gx +
sparse(Tcsc.bus1(a),Tcsc.x2(a),a1(a).*DB(a).*T2(a)./T3(a),2*Bus.n,DAE.n);
    DAE.Gx = DAE.Gx +
sparse(Bus.n+Tcsc.bus1(a),Tcsc.x2(a),V1(a).*a2(a).*DB(a).*T2(a)./T3(a),2*Bus.n,DAE.
n);
    DAE.Gx = DAE.Gx + sparse(Tcsc.bus2(a),Tcsc.x2(a),-
a1(a).*DB(a).*T2(a)./T3(a),2*Bus.n,DAE.n);
    DAE.Gx = DAE.Gx +
sparse(Bus.n+Tcsc.bus2(a),Tcsc.x2(a),V2(a).*a2(a).*DB(a).*T2(a)./T3(a),2*Bus.n,DAE.
n);

   end
  end

end

% --------------------------------------------------------------------------------
function Be = tcsca(af,xC,xL) % Be(alpha)

kx1 = sqrt(xC./xL);
kx2 = kx1.*kx1;
kx3 = kx2.*kx1;
```

```
kx4 = kx3.*kx1;
ckf = cos(kx1.*(pi-af));
skf = sin(kx1.*(pi-af));
s2a = sin(2*af);
caf = cos(af);
saf = sin(af);
Be = (pi*(kx4-2*kx2+1).*ckf)./(xC.*((pi*kx4-pi-2*kx4.*af+2*af.*kx2- ...
     kx4.*s2a+kx2.*s2a-4*kx2.*caf.*saf).*ckf -4*kx3.*caf.*caf.*skf));

% ------------------------------------------------------------------------------
function DB = tcscda(af,xC,xL) % -dBe/d(alpha)

kx1 = sqrt(xC./xL);
kx2 = kx1.*kx1;
kx3 = kx2.*kx1;
kx4 = kx3.*kx1;
ckf = cos(kx1.*(-pi+af));
skf = sin(kx1.*(-pi+af));
ck2 = ckf.*ckf;
c2a = cos(2*af);
s2a = sin(2*af);
caf = cos(af);
saf = sin(af);
ca2 = caf.*caf;
DB = -2*pi*(-kx4+2*kx2-1).*(2*skf.*skf.*kx1.*kx3.*ca2-ck2.*kx4+ck2.*kx2- ...
     ck2.*kx4.*c2a+ck2.*kx2.*c2a+2*ck2.*kx2.*saf.*saf-2*ck2.*kx2.*ca2- ...
     4*ckf.*kx3.*caf.*skf.*saf+2*kx3.*ca2.*ck2.*kx1)./xC./(ckf.*pi.*kx4- ...
     ckf.*pi-2*ckf.*kx4.*af+2*ckf.*af.*kx2-ckf.*kx4.*s2a+ckf.*kx2.*s2a- ...
     4*ckf.*kx2.*caf.*saf+4*kx3.*ca2.*skf).^2;

% ------------------------------------------------------------------------------
% function for creating warning messages
function tcscwarn(idx, msg)
global Tcsc
fm_disp(strcat('Warning: TCSC #',int2str(idx),' between buses #', ...
            int2str(Tcsc.bus1(idx)),' and #',int2str(Tcsc.bus2(idx)),msg))
```

APPENDIX 4

Sl No	Load (Amps)	Pressure in BAR	22/11KV Bus Voltage	Freque ncy	I	II	III	IV	V	22/11KV in Amps	Station Pf	Load in MW	Room Temp°c	Remar MVA
1	38	6.6	22.8	49.9	25	50	30	20	65	190	0.78	5.85	31	7.50
2	38	6.6	22.8	49.7	25	50	30	20	65	190	0.78	5.85	31	7.50
3	44	6.6	22.4	49.7	30	55	35	20	80	220	0.79	6.74	31	8.53
4	46	6.6	22	50	20	55	45	20	90	230	0.82	7.18	31	8.76
5	42	6.6	22	49.7	15	55	40	15	85	210	0.77	6.16	30	8.0
6	40	6.6	22	49.9	25	55	40	15	65	200	0.81	6.17	30	7.62
7	48	6.6	22.4	50	20	60	45	25	90	240	0.75	6.98	30	9.31
8	58	6.6	22.2	49.3	40	65	50	25	11 0	290	0.83	9.25	31	11.15
9	42	6.6	22.4	49.7	30	50	40	20	70	210	0.76	6.20	31	8.17
10	44	6.6	22.4	49.9	20	60	40	20	80	220	0.80	6.82	31	8.53
11	50	6.6	22	49.8	25	60	50	25	90	250	0.81	7.71	31	9.52
12	52	6.6	22	49.5	40	65	40	25	90	260	0.84	8.32	32	9.90
13	54	6.6	22	49.6	35	65	50	25	95	270	0.84	8.64	31	10.28
14	42	6.6	22.8	49.9	30	55	35	20	70	210	0.78	6.46	31	8.29

		Capacity	Peak
1. Transformer Load	:	20MVA	12.19MVA
		Max (KV)	Min (KV)
2. Voltage profile	:	HV 114 LV 22.8	109 21.8
3. Power factor	:	0.86(Max)	0.67(Min)
4. Minimum Power factor	:	0.75	
5. Number of feeder	:	5	

6. Consumer Disturbance factor [CDF]: 7.5 for 22KV

i) Average tripping in station per feeder per month (T) in numbers:
21 / (5*3) = 1.4

ii) Sum of total energy loss in all feeders of substation (L) in MWhr:
(1.63*0.216) + (2.85*0.566) + (1.89*0.70) + (0.99*0.10) + (3.88*0.1) = 3.775MWhr

iii) Sum of feeder capacity(C) in MW:
1.63 + 2.85 + 1.89 + 0.99 + 3.88 = 11.24MW

Index (%) = [(T) (L) / min Pf * C * 24 * M * 30] * CDF* 100

$$= \left[\frac{1.4 * 3.775}{0.75 * 11.24 * 24 * 3 * 30} \right] * 7.5 * 100 = 0.217\%$$

7. 22KV feeder	:	Line loss in (%)		
		HT	LT	Total
		12.05%	4.10%	16.15%

CALCULATION

Connected load : 15380 KVA
Power factor : 0.86
Peak Load : 125Amps
Total hours : 2160hrs
Period study : 1-1-2005 to 31-3-2005
Energy sent out: 52, 53900 units

$DF = 15380 / (\sqrt{3} * 22 8 125) = 3.22$

$LF = 5253900 / (\sqrt{3} * 22 * 125 * 0.86 * 2160) = 0.5938$

LLF = 0.8(0.5938)² + 0.2 * 0.5938 = 0.4008

A : 1-2 15380KVA – 11.787Km – 0.584
B : 2-3 2688KVA – 6.626Km – 0.977

$$=\left[\frac{15380}{22*3.22}\right]^2*\frac{11.787*0.584}{1000}=324.46$$

$$=\left[\frac{2688}{22*3.22}\right]^2*\frac{6.626*0.977}{1000}=9.320$$

333.78

L1 = 334 * 0.4008 * 2160 = 239153Units
L2 = (45*0.320) + (45*1.500) * 2160 = 176904
= (51*0.28) + (51*0.935) * 2160 = 133844
= (18*0.210) + (18*0.650) * 2160 = 33436

344184

% of DT Loss = 34418 – 5253900 = 6.55%

B = L1+L2 = 239153 + 344184 = 6, 33, 337 units
C = P.KVA *Pf * A = 4763 * 0.86 * 334 =4430
D = C*LF*Hrs = 4430 * 0.5938 * 2160 = 56, 81,953
L = B / D = 11.14%

Hut : 405*6*0.040*90 = 8748units
Agl : 6637061KW*3*90= 1712033units
Metered Energy = 2604285units

4405066units

Total loss: 5253900 ~ 4405066 = 848834units

$$\text{\% of Total loss} = \frac{848834}{5253900}*100=16.15\%$$

$$\text{HT Loss} = \frac{633337}{5253900}*100=12.05\%$$

$$\text{LT Loss} = \frac{5253900-4405066-633337}{5253900}=4.10\%$$

Total Loss = HT + LT = 16.15%

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on

CUTTING EDGE TECHNOLOGIES IN POWER CONVERSION AND INDUSTRIAL DRIVES (PCID – 2005)

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March 25 – 26, 2005

To

Date: 21-02-2005

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Title of paper : IMPROVEMENT OF POWER TRANSFER CAPABILITY USING TCSC

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