LOAD FLOW STUDY AND TRANSIENT STABILITY STUDY OF A MULTI-MACHINE SYSTEM USING STATCOM

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PROJECT

Submitted in partial satisfaction of the requirements for the degree of

MASTER OF SCIENCE

in

ELECTRICAL AND ELECTRONIC ENGINEERING

at

CALIFORNIA STATE UNIVERSITY, SACRAMENTO

FALL 2009
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Abstract

LOAD FLOW AND TRANSIENT STABILITY STUDY OF MULTI-MACHINE SYSTEM USING STATCOM

by

SURYA YERRAMILLI

In this modern age the power system is becoming increasingly large and much more complicated in its operation. Maintaining synchronism between various parts of power system is becoming cumbersome process, which arises stability problems in power system operations. It’s been made mandatory to consider the stability aspects. Power system operators should consider not only economic load dispatch but also stability aspects which are most essential.

The load flow and the transient stability studies constitute the major analytical approach to the study of power system and its electromechanical dynamic behavior. These studies are carried out by numerical iterative methods, which give accurate results and can be used for any degree of modeling sophistication.

In this project the Optimal Power flow and the classical model of the synchronous machine are used to study the stability of the power system with and without incorporating FACTS devices. A flexible alternating current transmission system
(FACTS) is a power electronic based system and other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability [27]. With the help of FACT devices, the Power system Performance can be improved, without any generation rescheduling or topology changes. Moreover with the use of FACTS device in the system, the line flows can be changed in such a way that thermal limits are not exceeded with losses minimized and stability margins increased and even contractual requirements can be fulfilled without violating economic dispatch. The impact of STATCOM on Optimal power flow and transient stability will be studied in this project.

For transient stability studies the classical model is considered in this project. It is the simplest modeling used in the power system dynamics and requires minimum amount of data and these studies can be conducted in a relatively short interval of time at minimum cost. Further these classical studies can be provided for useful online information.

____________________________, Committee Chair
Dr. John Balachandra

____________________________
Date
ACKNOWLEDGMENTS

I take this opportunity to thank all the people who are responsible for the successful completion of this project.

I express my sincere gratitude to Dr. John Balachandra, for his unending support and encouragement and for giving me an opportunity to work under his guidance. This project helped me learn something very new, which I haven’t learned in my coursework.

I am indebtedly thankful to Dr. Preetam Kumar, Graduate Coordinator, for offering his helping hand as a Second-Reader and for providing his valuable suggestions to make this project successful.

Thanks are due to all my friends on Campus who made my stay here in Sacramento memorable: Jaipaul Vasireddy, Vijay Venkata Lakkaraju, Sriram Akurati, Vijaya Yadav, Sridhar Nayakwadi, Navaneeth Beeram, Sankeerth Katkam, Soma NarisimhaRaju, Gogikar Geetha Malikraj, Pranav Cherupalli, Kuladeep Jogeswar Nadiminti, Vakula Peesari, Praveena Jakkula, Chakravarthy Kodali, Mazhar Ali, Parthiv Karri and Ashwin Hanumakonda.

I would also like to thank Srikanth Potluri, my mentor at Intel, for his constant support and motivation in making this project successful.

I would also like to thank all my friends at India who had supported and encouraged me to pursue my Master’s in United States.
I would like to thank my father, Kanakaji Rao; my mother, Venkata Satyavthi; and my dear sisters Archana & Prasanna and my brother-in-law Vyakarnam Shankar for all their faith and confidence in me to pursue a Master’s program in the United States. I am indebted to them for their unending love and blessings throughout my work.
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Chapter 1

INTRODUCTION

1.1 Load Flow

In present day’s scenario of highly complex and interconnected power systems, there is a great need to improve electric power utilization while still maintaining reliability and security. Load flow study in power system parlance is the steady state solution of the power system network. The main information obtained from this study comprises the magnitudes and phase angles of load bus voltages, reactive powers at generators buses, real and reactive power flow on transmission lines, other variables being known. Usually a generating station is not situated near the load center, but it may be away from load center due to various circumstances. In order to meet the ever-growing power demand, utilities prefer to rely on already existing generation and power export/import arrangements instead of building new transmission lines which are restricted by various constraints. On the other hand, power flows in some of the transmission lines are well below their thermal limits, while certain lines are overloaded, which has an overall effect of deteriorating voltage profiles and decreasing system stability and security. In addition, existing traditional transmission facilities, in most cases, are not designed to handle the control requirements of complex, highly interconnected power systems. This overall situation requires the review of traditional transmission methods and practices, and the creation of new concepts, which would allow the use of existing generation, and transmission lines up to their full capabilities without reduction in system stability and
security. Another reason that is forcing the review of traditional transmission methods is the tendency of modern power systems to follow the changes in today’s global economy that are leading to deregulation of electrical power markets in order to stimulate competition between utilities.[34, 35]

1.2 Power System Stability

Modern Electric Power system is a complex network of synchronous generators, transmission lines and loads. [21] With changes in generation schedules and load, the system characteristics will vary. Electrical Utilities started as stand-alone systems and with increasing growth in the neighboring utilities and upon their addition to the network began to form high interconnected systems. This facilitated the need to draw on each other’s generation reserves in required times. The interconnection improved reliability but has given birth to instability issues as the disturbances can propagate through the system. Depending on the magnitude of disturbance the system can become transiently unstable. A good power system should have the ability to regain its normal operating conditions even after the disturbance, as the ability to supply uninterrupted electricity determines the quality of a power system. Stability of a power system is considered as a very important aspect for research. [1, 2, 3, 21].

Power system stability can be defined as the ability of synchronous machines to remain in synchronism with each other following a major disturbance [1]. The possible
disturbances being the line faults, generator, line outages, load switching and etc…

Stability is characterized by the capability of power system to remain in synchronism for the possible disturbances. The stability studies are classified into steady state stability, transient stability and slowly growing stability depending on the order of magnitude and type of disturbance. [4, 5, 6, 21]. The transient stability of a system can be improved by using FACT Controllers.

1.3 FACTS Controllers

Flexible AC Transmission Systems (FACTS) devices as defined by IEEE as “power electronic based controllers and other static equipment which can regulate the power flow and transmission voltage through rapid control action”. In earlier days power system control was only based on generator control and the controlling ability on the transmission lines was meager. With advent of FACTS controllability of transmission line impedance, both series and shunt was made possible. The performance of long distance AC transmission lines can be improved by using FACTS devices in the Power system. The technology was later developed using FACTS devices to regulate Power flow in the system as well. Power transmitted in a power system depends upon the impedance in lines and on the voltages and angles at both sending and receiving ends. Different FACTS controllers can influence these parameters to regulate the power flow in interconnected systems. STATCOM a shunt connected FACTS application can facilitate the fast voltage control and the reactive power control in a Power system. [27, 28, 29, 21]
Chapter 2

FACTS IN POWER SYSTEM

2.1 General

The controllability on one or more power flow arguments aroused the possibility to control active as well as reactive power flow in the transmission systems. The arguments referred in the power flow are line impedance, magnitude of voltages on both sending and receiving end and also the angles between voltages. [23, 30]

In earlier times, power systems were designed to be self-sufficient and were very simple interconnected systems. The AC power flow between the power systems was rarely unusual as the AC transmission lines did not have the capability to handle dynamic changes in the system and these problems were usually solved by adapting generous stability margins. But now in today’s world with the advent of high complex interconnected systems the system loadability and security can be increased to an extent by number of different approaches. The common practice is to install the shunt capacitors on the receiving end side to improve the voltage levels and also insertion of series capacitors to reduce transmission line reactance, which would eventually increase the power transfer capability of lines. To introduce an additional phase shift between sending and receiving end voltages, phase shifting transformers are applied. The variability of these parameters were regulated mechanically and therefore the regulation was slow. By mechanically varying the parameters was good enough for the steady state operation but with increase in complexity of the Power system dynamic operation was pre-dominant
and the time response as in varying parameters mechanically is too slow to damp the transient oscillations. [14, 15, 18, 31]

This concept and advances in the field of power electronics led to a new approach introduced by the Electric Power Research Institute (EPRI). Called Flexible AC Transmission Systems or simply FACTS, it was an answer to a call for a more efficient use of already existing resources in present power systems while maintaining and even improving power system security. [30.31]

2.2 Basic Principles of Active and Reactive Power Flow Control

Active (real) and reactive power in a transmission line depend on the voltage magnitudes and phase angles at the sending and receiving ends as well as line impedance. To understand the basic concept behind the FACTS controllers as simple model is considered in Fig 2.2.1. The sending and receiving end voltages are assumed to be fixed and can be interpreted as points in large power systems where voltages are “stiff”. Assuming that the resistance of high voltage transmission lines are very small, there is equivalent reactance connected in between sending and receiving ends. The receiving end is modeled as an infinite bus with a fixed angle of 0°. [23, 28, 34]

\[
S_R = V_R I_R^* + Q_R = V_R I_R^* 
\]

\[
P_R = \frac{V_R^2}{X} \sin \delta 
\]

……………… (2.2.1)

……………… (2.2.2)
Similarly, for the sending end:

\[ P_s = \frac{V_s V_r}{X} \sin \delta - \sqrt{s} V_r \sin \delta \quad \text{............... (2.2.4)} \]

\[ Q_s = \frac{V_s^2 - \sqrt{s} V_r \cos \delta}{X} \quad \text{............... (2.2.5)} \]
Where $V_S$ and $V_R$ are the magnitudes (in RMS values) of sending and receiving end voltages, respectively, where $\delta$ is the phase-shift between sending and receiving end voltages. [28, 32, 34]

The system is assumed to be a lossless system and so the equations for sending and receiving active power flows, $P_S$ and $P_R$, are equal. The maximum active power transfer occurs, for the given system, at a power or load angle $\delta$ equal to $90^\circ$ which can be seen in the figure 1.1(a). Maximum power occurs at a different angle if the transmission losses are included. The system is stable or unstable depending on whether the derivative $dP/d\delta$ is positive or negative. The steady state limit is reached when the derivative is zero. [28, 29, 32, 34]

In practice, a transmission system is never allowed to operate close to its steady state limit, as certain margin must be left in power transfer in order for the system to be able to handle disturbances such as load changes, faults, and switching operations. The intersection between a load line representing sending end mechanical (turbine) power and the demand line defines the steady state value of $\delta$. The angle can be increased by a small increase in mechanical power at the sending end. With increasing load demands the angle goes beyond $90^\circ$ and results in less power transfer. This accelerates the generator and further increases the angle making the system unstable. However, the increased angle $\delta$ increases the electric power to correlate the mechanical increased power. The concepts of
dynamic (small signal stability) or Transient (large signal stability) are used to determine the appropriate margin for the load angle $\delta$. [23, 28, 29, 32, 34]

By the IEEE definition, “dynamic stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance such as a fault or loss of generation”. Typical power transfers correspond to power angles below 30°; to ensure steady state rotor angle stability, the angles across the transmission system are usually kept below 45°. Inspecting the equations little deeper reveals that the real or active power transfer depends mainly on the power angle and also reactive power requirements in both sending and receiving ands typically require high power transfers. From this information we can conclude that reactive power transfer depends mainly on voltage magnitudes, with flows from the highest voltage to the lowest voltage, while the direction of active power flow depends on the sign of the power angle. [1, 37, 38, 39, 40]

Another interesting observation is on the dependability on reactance. The maximum power transfer $P_{\text{max}}$ and the angle between two ends vary upon variation of reactance. The regulation of power flow is also possible by varying the sending and receiving end voltages. For a given power flow, a change of $X$ also changes the angle between the two ends. Regulating the magnitudes of sending and receiving ends voltages, $V_S$ and $V_R$, respectively, can also control power flow in a transmission line. From the equations of reactive power 2.2.4 & 2.2.5, it can be concluded that the regulation of voltage magnitude
has much more influence over the reactive power flow than the active power flow. [1, 37, 38, 39, 40]

2.3 Different FACTS Controllers

Basically the family of FACTS controllers is classified into two types. [27, 32, 33, 36]

(i) Series Controllers
(ii) Shunt Controllers

Definitions for various Series Controllers:

(i) Static Synchronous Series Compensator (SSSC): A static, synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power. The S\textsuperscript{3}C may include transiently rated energy storage or energy absorbing devices to enhance the dynamic behavior of the power system by additional temporary real power compensation, to increase or decrease momentarily, the overall real (resistive) voltage drop across the line.

(ii) Thyristor Controlled Series Capacitor (TCSC): A capacitive reactance compensator which consists of a series capacitor bank shunted by thyristor controlled reactor in order to provide a smoothly variable series capacitive reactance.
(iii) Thyristor Controlled Series Reactor (TCSR): An inductive reactance compensator which consists of a series reactor shunted by a thyristor controlled reactor in order to provide a smoothly variable series inductive reactance.

(iv) Thyristor Switched Series Capacitor (TSSC): A capacitive reactance compensator which consists of a series capacitor bank shunted by thyristor switched reactor to provide a step-wise control of series capacitive reactance.

(v) Thyristor Switched Series Reactor (TSSR): An inductive reactance compensator which consists of series reactor shunted by thyristor switched reactor in order to provide a step-wise control of series inductive reactance.

Definitions of various Shunt Controllers:

(i) Battery Energy Storage System (BESS): A chemical-based energy storage system using shunt connected, voltage sourced converters capable of rapidly adjusting the amount of energy which is supplied to or absorbed from an ac system.[32]

(ii) Static Synchronous Compensator (STATCOM): A static synchronous generator operated as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage.

(iii) Static Synchronous Generator (SSG): A static, self-commutated switching power converter supplied from an appropriate electric energy source and operated to produce a set of adjustable multi-phase output voltages, which may be coupled to
an ac power system for the purpose of exchanging independently controllable real and reactive power.

(iv) Static Var Generator or Absorber (SVG): A static electrical device, equipment, or system that is capable of drawing controlled capacitive and/or inductive current from an electrical power system and thereby generating or absorbing reactive power.

(v) Thyristor Controlled Reactor (TCR): A shunt-connected, thyristor-controlled inductor whose effective reactance is varied in a continuous manner by partial-conduction control of the thyristor valve.

(vi) Thyristor Switched Capacitor (TSC): A shunt-connected, thyristor-switched capacitor whose effective reactance is varied in a step-wise manner by full or zero conduction operation of the thyristor valve.

(vii) Thyristor Switched Reactor (TSR): A shunt-connected, thyristor-switched inductor whose effective reactance is varied in a step-wise manner by full or zero conduction operation of the thyristor valve.

2.4 Reactive power compensation with STATCOM

The amount of reactive power compensation provided by any FACTS device depends on the voltage at the bus. STATCOM can provide the maximum rated compensating current even at very low voltages. STATCOM also are equipped with transient capability which is available for a short period of time and this extra capability allows STATCOM to decide the maximum reactive power that can be supplied. [41]
2.5 STATCOM Theory:

STATCOM defined by IEEE as “A static synchronous generator operated as a shunt connected static var compensator whose capacitive voltage or inductive output current can be controlled independent of the ac system voltage.” [33]

A STATCOM is a controlled reactive power source. It provides voltage support by generating or absorbing reactive power at the point of common coupling without the need of large external or capacitor banks. The basic voltage source converter scheme is shown in figure 2.5.1. [23, 37]
The charged capacitor $C_{dc}$ provides a dc voltage to the converter, which produces a set of controllable three phase output voltages with frequency of the ac power system. By varying the amplitude of the output voltage $U$, the reactive power exchange between the converter and the AC system can be controlled. If the amplitude of the output voltage $U$ is increased above that of the AC system $U_T$, a leading current is produced, i.e. the STATCOM is seen as a conductor by the system and reactive power is generated. By decreasing the amplitude of the output voltage below that of AC system, a lagging
current results and the STATCOM is seen as an inductor. In this case reactive power is absorbed. If the amplitudes are equal no power exchange takes place. [23.37]

A practical converter is not lossless. The mechanism of phase angle adjustment can also be used to control the reactive power generated or absorbed by increasing or decreasing the capacitor voltage $U_{DC}$ and thereby the output voltage $U$. The derivation of the formula for the transmitted active power employs considerable calculations. [23.37]

![Fig 2.5.2: Static Synchronous Compensator V-I Characteristics][33]
The characteristics of STATCOM shown in fig 2.6.1 tells very clearly that it has the ability to support a very low system voltage; down to about 0.15 per unit, which is the value associated with the coupling transformer reactance. This is in strong contrast with that of a SVC when compared, which at full capacitive output becomes an uncontrolled capacitor bank. A STATCOM can support system voltage at extremely low voltage conditions as long as the dc capacitor can retain enough energy to supply losses. [23, 32, 33, 37].
Chapter 3

MODELING OF STATCOM AND POWER FLOW SOLUTION

3.1 Modeling of STATCOM:

The STATCOM is comprised of one voltage controlled source converter along with its associated shunt connected transformer. As there are no moving parts in STATCOM, it can be considered as a STATIC counterpart of rotating synchronous condenser. The absence of mechanical rotating parts makes STATCOM generate or absorb power at a faster rate unlike a regular synchronous generators [22, 42]

![VSC Diagram](image-url)

*Fig 3.1.1: VSC CONNECTED TO THE AC NETWORK VIA A SHUNT CONNECTED TRANSFORMER [22]*
The figures 3.1.1 and 3.1.2 represents the schematic view of STATCOM and the equivalent circuit of it respectively. Fig 3.1.2 also corresponds to the Thevenin equivalent as seen from bus k, with the voltage source $E_{VR}$ being the fundamental frequency component of the VSC output voltage, resulting from the product of $V_{DC}$ and $m_a$ [22, 42].

In steady-state fundamental frequency studies the STATCOM may be represented in the same way as a synchronous condenser, which in most cases is the model of a synchronous generator with zero active power generation. A more flexible model may be realized by representing the STATCOM as a variable voltage source $E_{VR}$, for which the magnitude and phase angle may be adjusted, using a suitable iterative algorithm, to satisfy a specified voltage magnitude at the point of connection with the AC network.
The shunt voltage source of the three-phase STATCOM may be represented by:

\[ E_{pR}^p = V_{pR}^p (\cos \delta_{pR} + j \sin \delta_{pR}). \]

Where \( p \) indicates phase quantities, a, b, c. The voltage magnitude, \( V_{pR}^p \) is given maximum and minimum limits, which are a function of the STATCOM capacitor rating.

However \( \delta_{pR} \) may take any value between 0 and \( 2\pi \) radians. With reference to the equivalent circuit shown in fig and assuming three-phase parameters, the following transfer admittance equation can be written:

\[
[I_k] = [Y_{rR} - Y_{rR}] [V_k E_{vR}]^T
\]

Where

\[
I_k = [I_k^a_L \gamma_k^a \quad I_k^b_L \gamma_k^a \quad I_k^c_L \gamma_K^a]^T
\]

\[
E_{vR} = [V_{rRL}^a \theta \delta_{rR}^a \quad V_{rRk}^b \theta \delta_{rR}^b \quad V_{rRk}^c \theta \delta_{rR}^c]^T
\]

and \( Y_{rR} \) is a diagonal matrix with \( Y_{rR}^a, Y_{rR}^b, \) and \( Y_{rR}^c \) in the principal diagonal.[22,42]

### 3.2 POWER FLOW MODEL:

The power flow equations for the STATCOM are derived below from first principle and assuming the following voltage source representations.

\[ E_{rR} = V_{rR} (\cos \delta_{rR} + j \sin \delta_{rR}) \]

Based on the shunt connection shown in figure above, the following may be written

\[ S_{vR} = V_{vR} I_{vR} = V_{vR} Y_{vR} (V_{vR}^* - V_{vK}) \]
The simplified model of active and reactive power equations are below. For a converter and bus K, respectively:

\[
P_{vR} = V_{vR}^2 G_{vR} + V_{vR} V_k [G_{vR} \cos (\delta_{vR} - \theta_k) + B_{vR} \sin (\delta_{vR} - \theta_k)],
\]

\[
Q_{vR} = -V_{vR}^2 B_{vR} + V_{vR} V_k [G_{vR} \sin (\delta_{vR} - \theta_k) - B_{vR} \cos (\delta_{vR} - \theta_k)],
\]

\[
P_k = V_k^2 G_{vR} + V_k V_{vR} [G_{vR} \cos (\theta_k - \delta_{vR}) + B_{vR} \sin (\theta_k - \delta_{vR})],
\]

\[
Q_k = -V_k^2 B_{vR} + V_k V_{vR} [G_{vR} \sin (\theta_k - \delta_{vR}) - B_{vR} \cos (\theta_k - \delta_{vR})].
\]

Using these power equations, the linearized STATCOM model is given below, where the voltage magnitude \( V_{vR} \) and phase angle \( \delta_{vR} \) are taken to be the state variables.[22,42]
3.3 MATLAB SIMULATION OF 5-BUS POWER SYSTEM USING NEWTON-RAPHSON’S METHOD:

The simulations in this book for power flow are done by using the matlab code available for load flow in Acha, C Fuerte-Esquivel, C. R., Ambriz-Perez, H. and Anglese-Camacho, C book [22]. The simulations are carried out in matlab and compared with IEEE test results.

3.3.1 SIMULATION WITHOUT STATCOM:

3.3.1(i) SIMULATION RESULTS FROM MATLAB:

<table>
<thead>
<tr>
<th>NODAL VOLTAGE</th>
<th>NORTH</th>
<th>SOUTH</th>
<th>LAKE</th>
<th>MAIN</th>
<th>ELM</th>
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</thead>
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<tr>
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<td>0.9841</td>
<td>0.9717</td>
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<td>-5.7649</td>
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</table>

3.3.1 (ii) IEEE TEST CASE RESULTS:

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<th>LAKE</th>
<th>MAIN</th>
<th>ELM</th>
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</thead>
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</table>
Fig 3.3.1 Five Bus test Network without STATCOM [22]
3.3.2 SIMULATION WITH STATCOM:

3.3.2 (i) SIMULATION RESULTS:

<table>
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<tr>
<th>NODAL VOLTAGE</th>
<th>NORTH</th>
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</table>

3.3.2 (ii) IEEE TEST CASE RESULTS:

<table>
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<tr>
<th>NODAL VOLTAGE</th>
<th>NORTH</th>
<th>SOUTH</th>
<th>LAKE</th>
<th>MAIN</th>
<th>ELM</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAGNITUDE (PU)</td>
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<td>-4.83</td>
<td>-5.11</td>
<td>-5.8</td>
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</tbody>
</table>
Fig 3.3.2 Five Bus test Network Upgraded with STATCOM [22]
3.4 POWER FLOW SOLUTION WITH STATCOM:

The results above clearly show the modeling of STATCOM for power flow studies provide better performance for the enhancement of dynamic and transient stability. The Power flow results indicate that, the STATCOM generates 20.5 MVAR in order to keep the Voltage magnitude at 1.p.u at Lake Bus. The slack generator reduces its reactive power generation by almost 6% compared with the base case, and the reactive power exported from North to Lake reduces by more than 30%. The largest reactive power flow takes place in the transmission line connecting North and South. And the generator connected at South increases its share of reactive power absorption compared with the base case. So, in summary the power flow results shows that STATCOM generates reactive power and maintains flat voltage profile. Active power flows are marginally affected and reactive is generated locally with installation of STATCOM. This proves that complex power flow can be controlled with STATCOM and the power flow can be controlled rapidly and in a flexible way by using it. [22]
4.1 General:
In transient stability studies, particularly those involving short periods of analysis in the order of a second or less, a synchronous machine can be represented by a voltage source, in back of transient reactance, that is constant in magnitude but changes its angular position. This representation neglects the effect of saliency and assumes constant flux linkages and a small change in speed [1, 3,26]

4.2 Simplified E' Model of Synchronous Machine:

\[
E' = E + x_{d}I_{t} + x'_{d}I_{t}
\]

\[\text{(4.2.1)}\]

Where

- \(E\) = Voltage back of transient reactance
- \(E_{t}\) = Machine terminal voltage
- \(I_{t}\) = Machine terminal current
- \(r_{a}\) = armature resistance
- \(x^{1}_{d}\) = transient reactance

The representation of the synchronous machine used for network solutions and the corresponding phasor diagram are shown in figure (4.1).
The saliency and changes in the field flux linkages can be taken into account by representing the effects of the three-phase ac quantities of a synchronous machine by components acting along the direct and quadrature axes. The direct axis is along the center line of the machine pole and the quadrature axis leads the direct axis by 90 electrical degrees. [1,3,26]

**Figure 4.1.1 Equivalent circuit of synchronous machine**[1]

**Figure 4.1.2 Phasor diagram of synchronous machine**[1]
4.3 Representations of loads:

Power system loads other than motors represented by equivalent circuits, can be treated in several ways during the transient period. The commonly used representations are either static impedances or admittance to ground, constant current at fixed power factor, constant real and reactive power, or a combination of these representations. [1,3,26]

The constant power load is either equal to the scheduled real and reactive busload or is a percentage of the specified values in the case of a combined representation. The parameters associated with static impedance and constant current representations are obtained from a load flow solution for the power system prior to a disturbance. The initial value of the current for the constant current representation is obtained from [1,3,26]

\[ I_{po} = \frac{P_{lp} - jQ_{lp}}{E_p^*} \]

Where \( P_{lp} \) and \( Q_{lp} \) are the scheduled busloads and \( E_p \) is the calculated bus voltage. The current \( I_{po} \) flows from bus P to ground i.e. to bus zero. The magnitude and power factor angle of \( I_{po} \) remain constant.[1,3,26]

The static admittance \( y_{po} \), used to represent the load at bus P can obtained from equation

\[ (E_p - E_o)^* y_{po} = I_{po} \]
Where $E_p$ is the calculated bus voltage and $E_o$ is the ground voltage equal to zero.

Therefore

$$y_{po} = \frac{I_{po}}{E_p} \quad \text{…………. (4.3.1)}$$

Multiplying both the dividend and divisor of the equation (4.3.1) by $E_p^*$ and separating the real and imaginary components

$$g_{po} = \frac{P_{Lp}}{e_p^2 + \gamma_p^2} \quad \text{and} \quad b_{po} = \frac{Q_{Lp}}{e_p^2 + \gamma_p^2}$$

Where

$$y_{po} = g_{po} - jb_{po}$$

### 4.4 NETWORK PERFORMANCE EQUATIONS:

The network performance equations used for load flow calculations can be applied to describe the performance of network during the transient period. Using the bus admittance matrix with ground as reference, the voltage equation bus $P$ is

$$E_p = \frac{(P_p - Q_p)L_p}{E_p^*} - \sum_{q=1 \atop q \neq P}^{\infty} p_q E_q \quad \text{……………… (4.4.1)}$$

The term $\frac{P_p - Q_p}{E_p^*}$ in equation (3.4.1) represents the load current at bus $P$. For the constant current load representation
\[
\frac{P_p - Q_p}{(E_p^k)^*} = j \cdot \phi_p \left( 1 + j \cdot \theta_p \right) \quad \text{.................. (4.4.2)}
\]

Where \( \phi_p \) is the power factor angle and \( \theta_p \) is the angle of voltage with respect to reference. When the constant power is used to represent the load \((P_p - Q_p)L_p\) will be constant but the bus voltage \(E_p\) will change every iteration. When the node at bus \(p\) is represented by a static admittance to ground, the impressed current at the bus is zero and therefore

\[
\frac{(P_p - Q_p)L_p}{E_p^*} = 0
\]

In using equation (4.4.1) to describe the performance of the network for a transient analysis, the parameters must be modified to include the effects of the equivalent elements required to represent synchronous and induction machines and loads. The line parameters \( Y_{L_{pq}} \) must be modified for the new elements and an additional line parameter must be calculated for each new network element. [1, 3, 26]

Let us consider the system shown in fig (4.2), which was used to illustrate the load flow solution techniques.
The model has two machines and a load at each bus representing all loads as static admittance to ground, the voltage equation for bus one is shown in Fig (4.2)

$$E_1 = - L_{12} E_2 - L_{13} E_3 - L_{14} E_4 - L_{10} E_0$$

Where

$$YL_{12} = \frac{\gamma_{12}}{L_1}$$
$$YL_{13} = \frac{\gamma_{13}}{L_4}$$
$$YL_{14} = \frac{\gamma_{14}}{L_1}$$

The elements $Y_{12}$, $Y_{13}$ and $Y_{14}$ from the bus admittance matrix of the network are the same as in load flow representation.
However,

\[ L_1 = \frac{1}{Y_{11}} \]

Where

\[ Y_{11} = Y_{12} + Y_{13} + Y_{14} + Y_{10} \]

include the static admittance representing the load. Since \( E_0 \) is zero, the line parameter \( YL_{10} \) does not have to be calculated.

The voltage equation for bus 2 is

\[ E_2 = -L_{21}E_1 - L_{25}E_5 - L_{26}E_6 - L_{28}E_8 \]

where bus 8 is a new bus. In this case the diagonal admittance elements for bus 2 is

\[ Y_{22} = Y_{21} + Y_{25} + Y_{26} + Y_{20} + Y_{28} \]

where \( Y_{20} \) is the static admittance representing the load and is the machine equivalent admittance. The formulas for the Gauss-Siedal iterative solution of the network shown in the above figure (4.2)

\[
\begin{align*}
E_1^{K+} &= -YL_{12}E_2^K - YL_{13}E_3^K - YL_{14}E_4^K \\
E_2^{K+} &= -YL_{21}E_1^{K+} - YL_{25}E_5^K - YL_{26}E_6^K - YL_{28}E_8 \\
E_3^{K+} &= -YL_{31}E_1^{K+} - YL_{35}E_5^K \\
E_4^{K+} &= -YL_{41}E_1^{K+} - YL_{46}E_6^K - YL_{47}E_7 \\
E_5^{K+} &= -YL_{52}E_2^{K+} - YL_{53}E_3^K \\
E_6^{K+} &= -YL_{62}E_2^{K+} - YL_{64}E_4^K 
\end{align*}
\]

The initial bus voltages are obtained from the load flow solution prior to the disturbance, these voltages for the new buses 7 and 8 are obtained from the equivalent circuit
representing the machine. Subsequent voltages for the buses are calculated from the differential equations describing the performance of the machines.[1,3,26]

During the iterative calculation the magnitudes and of the bus voltages behind the machine equivalent admittances are held constant. If a three phase is simulated the voltage of faulted bus is set to zero and held constant. If the bus impedance matrix is used for a transient stability study, ground is usually taken as reference because all network bus voltages, except at the faulted bus, change during the transient period. To eliminate the need to modify the bus impedance matrix for a change in the reference bus, ground is used also as reference in the prefault load flow calculation.[1,3,26]

When ground is used as reference for the load flow calculation and the loads are represented solely as current sources, the bus impedance matrix will include only the capacitor, reactor and the line charging elements to ground. In this case the bus impedance matrix is ill conditioned and convergence of the solution is usually not obtained. On the other hand if the loads are represented solely as impedance to ground to improve the convergence characteristic then these impedances and the bus impedance matrix must be modified during the iterative solution for changes in bus voltages. To overcome this difficulty only a portion of each bus load is represented as impedance to ground. The remaining portion of the load can be represented as current source which varies with the bus voltage so that the total bus current satisfies the scheduled load power.
After the load flow solution is obtained, the bus impedance matrix must be modified to include the new network elements representing the machines and to account for the changes in representation of loads. These modifications can be made by using the algorithm described. Each element representing a machine is a branch to a new bus, and each element representing a load change is a link to ground. [1,3,26]

The iteration formula for the performance of the network during the transient period using ground as reference is

\[
E^K_{P+1} = \sum_{q=1}^{n+m} Z_{pq} I_q \\
\]

\[ p = 1,3,26 \]

Where \( n \) is the number of network buses, \( m \) is the number of buses behind the equivalent machine impedances and bus \( f \) is the faulted bus. The current vector \( I_q \) is composed of load currents from either the constant currents or constant power representation and the currents obtained from machine equivalent circuits.\[1,3,26\]

The application of the bus impedance matrix, only those rows and columns corresponding to machines, constant power and constant current sources need to be retained for the network solution. All rows and columns would have to be maintained,
however its system voltages and power flows are required during the transient calculations. [1, 3, 26]

The procedures required using the bus impedance and admittance matrices and representing each machine as a voltage behind the machine impedance is an application of Thevinin’s theorem. An alternate method is to represent the machine as a current source between the machine terminal bus and ground and in parallel with the machine impedance. This is an application of Norton’s Theorem. This eliminates the need to establish the additional bus behind the impedance of each machine. The machine currents are calculated by using the internal machine voltages and the machine impedances. These currents are held constant during network iterative solution. [1, 3, 26]
5.1 Multi-Machine Transient Stability Studies:

The equal-area criterion cannot be used directly in systems where three or more machines are represented. Although the physical phenomena observed in the two machines basically reflect that of the multi-machine case, nonetheless, the complexity of the numerical computations increases with the number of machines considered in a transient stability study. When a multi-machine system operates under electro-mechanical transient conditions, inter-machine oscillations occur between the machines through the medium of the transmission system, which connects them. If any one machine could be considered to act alone as the single oscillating source, it would send into the interconnected system an electro-mechanical oscillation determined by its inertia and power. A typical frequency of such oscillation is of the order of 1 to 2 Hz and this is super-imposed upon the nominal 50 Hz frequency of the system. When many machine rotors are simultaneously undergoing transient oscillation, the swing curves will reflect the combined presence of many such oscillations. Therefore, the transmission system frequency is not unduly perturbed from nominal frequency, and the assumption is made that the 50Hz network parameters are still applicable. [1, 2, 3, 26]

Aligned with such complexity in system modeling which evolve problems involving large disturbances which do not allow the linearization process to be used and the non-
linear differential and algebraic equations must be solved by direct methods or by iterative step by step procedures. These transient stability problems may be analyzed by first swing stability studies, which are based on reasonably simple generated model without representation of control systems. [1, 2, 3, 26]

5.2 Classical transient stability studies:
The classical model is used to study the transient stability of a power system for a period of time during which the dynamic behavior of the system is largely dependent on the stored energy in the rotating inertias. Usually the time period under study is the first second following a system fault. If the machines of the system are found to remain in synchronism with in the first second, the system is said to be stable. This is the simplest model used in stability studies and requires minimum amount of data. [1, 2, 3, 26]

To ease the complexity system modeling and the computational burden the following assumptions are made in developing the classical model are as follows: [26]

1) The mechanical power input to each machine remains constant during the entire period of the swing curve computation.
2) Damping or asynchronous power is negligible.
3) Each machine may be represented by a constant transient reactance in series with a constant transient voltage
4) The mechanical rotor angle of each machine coincides with the electrical phase angle of the transient voltage.

5) All loads may be considered as shunt impedances to ground with values determined by conditions prevailing immediately prior to the transient conditions.

The system stability model based on the assumptions is called the classical stability model and studies which use this model, are called classical stability studies or first swing stability studies. [1, 26]

This model is useful for stability analysis but is limited to the transients for only the “First swing” or for periods on the order of one second. Assumption 2 can be improved by assuming a linear damping characteristic. A damping torque $D\omega$ is frequently added to the inertial torque in the swing equation. [1, 26]

The damping co-efficient $D$ includes the various damping torque components, both mechanical and electrical values of damping co-efficient. The modified study state model of synchronous machine is shown in fig (5.1) for the purpose of transient stability analysis as per the assumption three. The reactance $X_d^l$ is a direct transient reactance. The constant voltage source $|E|\angle$ determined from the initial conditions (i.e. pre disturbance power flow conditions). [1, 26]
During the transient the magnitude of $|E|$ is held constant with a variation of angle $\delta$ is governed by
\[ M \dot{\delta} \cdot D \dot{\delta} \cdot P_G(\delta) = \dot{P}_M \] \hfill (5.2.1)

Load representation can have a marked effect on stability results. The representation of loads has constant impedances is usually made for simplicity based on assumption 5. This assumption allows us to eliminate the algebraic network equations and reduce the system of equations for the multi machine system to a system consisting of only differential equations. [1, 26]
5.3: Numerical Methods for Solution of Swing equation:

In general, methods of numerical integration employ a step-by-step process to determine a series of values for each dependent variable corresponding to a selected set of values of the independent variable. The usual procedure is to select values of the independent variable at fixed intervals. The accuracy of a solution by numerical integration depends both on the method chosen and the size of interval. In this project to solution differential equations modified Euler’s method.[1]

5.3.1 Modified Euler method:

When a machine is represented by a voltage of constant magnitude back of transient reactance, it is necessary to solve two first-order differential equation to obtain the changes in the internal voltage angle $\delta_i$ and machine speed $\omega_i$. Thus for an m machine problem where all machines are represented in the simplified manner, to is necessary to solve $2m$ simultaneous differential equations. These equations are

$$\frac{d\delta_i}{dt} = \pi_m - \pi$$  \hspace{1cm} \text{(5.3.1)}

$$\frac{d\omega_i}{dt} = \pi_i \left( b_{mi} - \delta_{qi(t)} \right) \hspace{1cm} i=1, 2, 3... m$$

If no governor action is considered, $P_{mi}$ remains constant and

$$P_{mi} = P_{mi(0)}$$
In the application of the modified Euler method the initial estimates of the internal voltage angles and machine speeds at time \( t + \Delta t \) are obtained from

\[
\delta_0^+ = \delta_i^+ + \frac{1}{\Delta t} \left| \omega \right| \Delta \quad \text{..........................(5.3.2)}
\]

\[
\omega_0^+ = \omega_i^+ + \frac{1}{\Delta t} \left| \omega \right| \Delta \quad \text{i=1, 2, 3...m \quad ......(5.3.3)}
\]

Where the derivatives are evaluated from equations (5.3.1) and \( P_e \) are the machine powers at time \( t \). When \( t = 0 \), the powers \( P_e \) are obtained from the network solution at the instant after the disturbance occurs. Second estimates are obtained by evaluating the derivatives at time \( t + \Delta t \). This requires that initial estimates be determined from the machine powers at time \( t + \Delta t \). These powers are obtained by calculating new component of the internal voltage from

\[
e_0^+ = E_i \cos \delta_i^+ \quad \text{.......................... (5.3.4)}
\]

\[
f_0^+ = E_i \sin \delta_i^+ \quad \text{.......................... (5.3.5)}
\]

Then the network solution is obtained holding fixed the voltages at the internal machine buses. When there is a three-phase fault on bus f, the voltage \( E_i \) also is held fixed at zero.
With the calculated bus voltages and the internal voltages, machine terminal currents can be calculated from

\[ I_{ij} = \frac{\Phi_{ij} + \gamma_{ij} + \frac{1}{jX'}}{\gamma_{ai} + \frac{1}{X'}} \]

and machine power from

\[ P_{ei} = \text{Re} \left( I_{ei}^* \Phi_{ei}^* \right) \]

The second estimates for the internal voltage angles and machine speeds are obtained from

\[
\delta = \delta + \left( \frac{\delta}{dt} + \frac{\delta}{dt} \right) \frac{1}{2} \\
\omega_i = \omega + \left( \frac{\delta_i}{dt} + \frac{\delta_i}{dt} \right) \frac{1}{2} \quad i=1,2,3\ldots m \quad \text{...... (5.3.6)}
\]

Where
The final voltages at time \( t + \Delta t \) for the internal machine buses are

\[
e'_i = E'_i \cos \delta \quad \text{i=1, 2, 3... m} \quad \text{......... (5.3.8)}
\]

\[
f'_i = E'_i \sin \delta \quad \text{i=1, 2, 3... m} \quad \text{......... (5.3.9)}
\]

Then the network equations are solved again to obtain the final system voltages at time \( t + \Delta t \). The bus voltages are used along with the internal voltages to obtain the machine currents and powers and network power flows. The time is advanced by the \( \Delta t \) and a test is made to determine if the switching operation is to be affected or the status of the fault is to be changed. If an operation is scheduled, the appropriate changes are made in network parameters or variables, or both. Then the network equations are solved to obtain system conditions at the instant after the change occurs. In this calculation the internal voltages are held fixed at the current values. Then estimates are obtained for the next time
increment. The process is repeated until \( t \) equals the maximum time \( T_{\text{max}} \) specified for the study. [1,3]

The sequence of steps for transient analysis by the modified Euler method and the load flow solution by the Gauss-Seidel iterative method using \( Y_{\text{BUS}} \) in flow chart. Shown also are the main steps of the preliminary calculations. The procedure shown assumes that all system loads are represented as fixed impedances to ground. [1,3]

When the effects of the saliency and the changes in field flux linkages are to be included in the representation of the machines the following differential equations must be solved simultaneously.[1,3]

\[
\frac{d\delta}{dt} = \frac{\pi}{\psi_{\text{mi}}} - \pi
\]

\[
\frac{d\omega}{dt} = \frac{\pi}{H_i} \psi_{\text{mi}} - \psi_{el}
\]

\[
\frac{dE'}{dt} = \frac{1}{\Gamma_{f_{i}i}} \psi_{f_{di}} - \psi_{ji} \quad i=1, 2, 3...m
\]

Again, if no governor action is considered, \( P_{\text{mi}} \) remains fixed and

\[
P_{\text{mi}} = \gamma_{\text{mi}}
\]

If the effects of the exciter control system are not included, \( E_{f_{di}} \) remains constant and
\[
E_{fdi} = \hat{Z}_{fdi}\hat{q}
\]

If each machine of the system is described by equation (5.3.10), \(3m\) simultaneous equations must be solved.

5.4: STATCOM in Power System:

To include the significant components in stability study it is necessary to represent the controller design adequately to represent the mathematical model of a power system. [21]

5.4.1 Synchronous generator and its Excitation System:

The synchronous generator is modeled through q-axis component of transient voltage and electromechanical swing equation representing motion of the rotor. The internal voltage equation of the generator is written as,

\[
e_q' = E_{fd} - \hat{Z}_q - x_d' \hat{q_d} \hat{I}_{d} \frac{1}{T_{do}}
\] ........................ (5.4.2.1)

where, \(e_q'\) subscript d and q represents the direct and quadrature axis of the machine, \(x_d'\) and \(T_{do}\) are the d-axis synchronous reactance, transient reactance and open circuit field constants, respectively. \(I_d\) is the current along the d-axis and \(e_q'\) is the voltage behind the transient reactance. [21]
Now the electromechanical swing equation is broken into two first order differential equations and is written as,

\[ \omega = \frac{1}{2H} \left[ P_m - \dot{\delta} - \frac{1}{2} \Omega \right] \] ................................. (5.4.2.2)

\[ \delta = \delta_0 \] .................................

where, the electrical power output is,

\[ P_e = \dot{\delta}_d I_d + \dot{\delta}_q I_q \] ................................. (5.4.2.3)

\( v_d \) and \( v_q \) are components of generator terminal voltage \( (V_t) \). \( P_m \) is the mechanical power input. \( H \) is the inertia constant in seconds, \( 2H = M \). \( \omega \) is the synchronous speed. [21]

The IEEE type ST is used for the voltage regulator excitation. The block diagram of the excitation system is shown in Fig. 3.2.

![Diagram](image)

*Fig. 5.4.2.1: Block diagram of excitation system [21]*
The dynamic model of the excitation system is,

$$E_{fd} = -\frac{1}{T_A} E_{fd} + \frac{K_A}{T_A} (V_m - \dot{V})$$

(5.4.2.4)

where, $K_A$ and $T_A$ are the gain and time constant of exciter, respectively. $V_{to}$ represents the steady state (reference) value of terminal voltage.[21]
Chapter 6

ALGORITHM AND FLOW CHART

6.1 Algorithm for Classical Transient stability study:

**Step 1:** Read the bus data i.e. bus codes, impedance, line charging admittance and the scheduled generation and loads of the given system.

**Step 2:** The Y bus matrix is calculated from the lines, transformer, STATCOM data and shunt element data and the load flow solution prior to the disturbance is calculated by using Newton-Raphson iterative method.

**Step 3:** If there is any switching action we have to modify the system data first and also, solve the network performance equations, calculate machine currents $I_i$ and the machine terminal powers $P_i, Q_i$ for all buses by using the equations (6.1.1), (6.1.2) and (6.1.3) respectively, otherwise go to **step 4**

\[
E_{p}^{k+1} = - \sum_{q=1}^{p-1} Y_{pq} E_{q}^{k+1} - \sum_{q=p+1}^{n} Y_{pq} E_{q}^{k} - \sum_{r=1}^{m} Y_{pr} E_{r}^{1}
\]

…………… (6.1.1)

\[p = 2, \ldots, n.\]

\[p \neq f \text{ (When fault on bus f)}\]
\[ I_{ti} = \left( E_t^i - \tilde{\gamma}_{ti} \right) \frac{1}{r_{ai} + \chi_i^t} \]  \hspace{1cm} \text{.........} \hspace{1cm} (6.1.2)

\[ i = 1, 2, 3... \]

\[ P_{ti} - jQ_{ti} = I_{ti} E_{ti}^* \]  \hspace{1cm} \text{.........} \hspace{1cm} (6.1.3)

\[ i = 1, 2, 3... \hspace{1cm} m \]

**Step 4:** Compute the inertial estimates of power angles, machine speeds and inertial estimates of voltages behind machine impedances all of them at \( t + \Delta t \) by using the equations (5.3.2), (5.3.3), (5.3.4) and (5.3.5).

**Step 5:** Solve the network performance equations and calculate machine currents \( I_{ti} \) and calculate the machine terminal powers \( P_{ti} \) and \( Q_{ti} \) for these machines by using equations (6.1.1), (6.1.2) and (6.1.3).

**Step 6:** Calculate final estimates of power angles and machine speeds and also find the estimates of voltages behind the machine impedance at \( t + \Delta t \) by using the equations (5.3.6), (5.3.7), (5.3.8) and (5.3.9), and solve the equation (6.1.1), (6.1.2) and (6.1.3).

**Step 7:** Advance the time \( t + \Delta t \) to \( t \) and test for the time limit, if it is less than \( T_{\text{max}} \) then go to step 3 otherwise print results.
6.2 Flow Chart for Modified Euler’s method [1]

Start

Calculate load flow to disturbances prior

Calculate load flow to disturbances prior

Calculate machine currents

\[ I_a = \frac{P_{ti} - Q_{ti}}{E^*_{ti}} \]

\[ i = 1, 2, \ldots, m \]

Calculate voltages behind machine equivalents

\[ E'_{i(0)} = E_{ti} + r_{ai}I_{ti} + jx'_{ai}I_{ti} \]

\[ i = 1, 2, \ldots, m \]

Set time \( t = 0 \)

Is there a switching operation or change in fault condition?

C

A

YES

B

D

Calculate initial estimates of power angles and machine speeds at \( t + \Delta t \)

\[ \delta_{i(t+\Delta t)} = \delta_{i(t)} + \frac{\gamma}{\Delta t} |_{(t)} \Delta \]

\[ \omega_{i(t+\Delta t)} = \omega_{i(t)} + \frac{\gamma}{\Delta t} |_{(t)} \Delta \]

\[ i = 1, 2, 3, \ldots, m \]

Calculate initial estimates of voltages behind machine impedances at \( t + \Delta t \)

\[ e'_{i(t+\Delta t)} = E'_{e} \cos \delta_{i(t+\Delta t)} \]

\[ f_{i(t+\Delta t)} = E'_{f} \sin \delta_{i(t+\Delta t)} \]

\[ i = 1, 2, 3, \ldots, m \]
Calculate machine currents
\[
I_{ti} = \frac{1}{r_{ai}} \left( E_i^* - E_{ti} \right) + jX_{di}
\]
i = 1, 2, ..., m

Modify system data

Set j = 0

Solve Network Performance equations
\[
E_{p+1}^{k+1} = \sum_{q=1}^{p-1} YL_{pq} E_{q+1}^{k+1} - \sum_{q=p+1}^{n} YL_{pq} E_{q}^{k} - \sum_{t=1}^{m} YL_{pt} E_{t+1}^{k}
\]
p = 1, 2, ..., n

Calculate machine terminal powers
\[
P_{ai} - jQ_{ai} = I_{ti} E_{ui}^*
\]
i = 1, 2, ..., m

Test j: 0
Equal

Test j: 1
Equal

Calculate final estimates of power angles and machine speeds at t + Δt
\[
\delta_{p+1, i} = \delta_{p, i} + \left( \frac{1}{2} \frac{d\delta}{dt} \right)_{p, i} + \left( \frac{1}{2} \frac{d\omega}{dt} \right)_{p, i}
\]
i = 1, 2, 3, ..., m

Set j = 1
Calculate final estimates of voltage Behind machine impedances and $t+\Delta t$

\[
e^{i\delta_{4+i}} = E', \cos \delta_{4+i},
\]

\[
f^{i\delta_{4+i}} = E', \sin \delta_{4+i},
\]

$i=1, 2, 3, ..., m$

Set $j=2$
Chapter 7

RESULTS

7.1 Case Study (Stable case):

In this case the machines are represented by detailed models and loads are modeled as constant admittances. The disturbances considered are three-phase faults at different buses.

A two-generator, five bus system is considered in which a 3-phase fault is created on machine-2, and this is cleared after 0.15 sec. Numerical integration of the swing equation are obtained with the help of digital computer by using modified Euler`s method with a time period of 1.0 sec. The swing curve is shown in fig (7.1) & (7.2). From that figures system is found to be stable.

7.2 Case Study (Unstable case):

In this case the three-phase fault is created on machine-2, and the fault is cleared after 0.2 sec. Numerical integration of the swing equations are obtained with the help of digital computer by using modified Euler`s method with a time period of 1.0 sec. and the swing curve is shown in fig (7.3) & (7.4). From that figures system is found to be unstable.

From these two cases we can infer that, if the fault is cleared within 0.15 sec the system is found to be stable and if clearance time is increased then the system is in unstable condition which is evident from the simulated results (7.3) and (7.4).
Fig 7.1: Relative Angle of Machine2 for a fault on Bus2 Cleared at 0.15sec, of a 5-Bus Power system with Stable case

Fig 7.2: Internal Voltage Angle of Machines for a fault on Bus2 Cleared at 0.15sec, of a 5-Bus Power system with Stable case
Fig 7.1: Relative Angle of Machine2 for a fault on Bus2 Cleared at 0.2sec, of a 5-Bus Power system with unstable case

Fig 7.2: Internal Voltage Angle of Machines for a fault on Bus2 Cleared at 0.15sec, of a 5-Bus Power system with unstable case
Table 7.1: Simulation results for fault on bus-2 cleared at 0.15 sec, for a 5-bus system with stable case

(Classical transient stability)

<table>
<thead>
<tr>
<th>Time in seconds</th>
<th>Relative rotor angles in degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7.24</td>
</tr>
<tr>
<td>0.05</td>
<td>14.51</td>
</tr>
<tr>
<td>0.1</td>
<td>32.18</td>
</tr>
<tr>
<td>0.15</td>
<td>50.77</td>
</tr>
<tr>
<td>0.2</td>
<td>56.41</td>
</tr>
<tr>
<td>0.25</td>
<td>47.9</td>
</tr>
<tr>
<td>0.3</td>
<td>27.08</td>
</tr>
<tr>
<td>0.35</td>
<td>-0.59</td>
</tr>
<tr>
<td>0.4</td>
<td>-25.61</td>
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<tr>
<td>0.45</td>
<td>-38.51</td>
</tr>
<tr>
<td>0.5</td>
<td>-34.86</td>
</tr>
<tr>
<td>0.55</td>
<td>-16.87</td>
</tr>
<tr>
<td>0.6</td>
<td>7.87</td>
</tr>
<tr>
<td>0.65</td>
<td>29.92</td>
</tr>
<tr>
<td>0.7</td>
<td>42.44</td>
</tr>
<tr>
<td>0.75</td>
<td>42.69</td>
</tr>
<tr>
<td>0.8</td>
<td>31.14</td>
</tr>
<tr>
<td>0.85</td>
<td>11.2</td>
</tr>
<tr>
<td>0.9</td>
<td>-10.49</td>
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<tr>
<td>0.95</td>
<td>-25.82</td>
</tr>
<tr>
<td>1</td>
<td>-29.06</td>
</tr>
</tbody>
</table>
Table 7.2: Simulation results for fault on bus-2 cleared at 0.15 sec, for a 5-bus system with stable case

(Classical transient stability)

<table>
<thead>
<tr>
<th>Time in seconds</th>
<th>Internal voltage angles</th>
<th>( \delta ) in degrees</th>
<th>( \delta ) in degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>12.15</td>
<td>19.39</td>
<td></td>
</tr>
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<td>0.05</td>
<td>12</td>
<td>26.51</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>12.26</td>
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</tr>
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<td>12.82</td>
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</tr>
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<td>62.39</td>
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<td>15.62</td>
<td>42.69</td>
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</tr>
<tr>
<td>0.35</td>
<td>16.85</td>
<td>16.26</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>18.01</td>
<td>-7.61</td>
<td></td>
</tr>
<tr>
<td>0.45</td>
<td>18.9</td>
<td>-19.6</td>
<td></td>
</tr>
<tr>
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<td>19.42</td>
<td>-15.44</td>
<td></td>
</tr>
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<td>0.55</td>
<td>19.52</td>
<td>2.64</td>
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<td>19.26</td>
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<td>18.78</td>
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<td>18.25</td>
<td>60.69</td>
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<td>17.81</td>
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<td>48.65</td>
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</tr>
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<td>0.85</td>
<td>17.33</td>
<td>28.53</td>
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</tr>
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<td>0.9</td>
<td>17.15</td>
<td>6.66</td>
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</tr>
<tr>
<td>0.95</td>
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<td>-8.99</td>
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</tr>
<tr>
<td>1</td>
<td>16.23</td>
<td>-12.83</td>
<td></td>
</tr>
</tbody>
</table>
Table 7.3: Simulation results for fault on bus-2 cleared at 0.2 sec, for a 5-bus system with unstable case

(Classical transient stability)

<table>
<thead>
<tr>
<th>Time in seconds</th>
<th>Relative rotor angles in degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7.24</td>
</tr>
<tr>
<td>0.05</td>
<td>14.51</td>
</tr>
<tr>
<td>0.1</td>
<td>32.18</td>
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<td>1487.89</td>
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<td>1636.94</td>
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</table>
Table 7.4: Simulation results for fault on bus-2 cleared at 0.2 sec, for a 5-bus system with unstable case
(Classical transient stability)

<table>
<thead>
<tr>
<th>Time in seconds</th>
<th>Internal voltage angles</th>
<th>( \delta ) in degrees</th>
<th>( \hat{\delta} ) in degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>12.15</td>
<td>19.39</td>
<td></td>
</tr>
<tr>
<td>0.05</td>
<td>12</td>
<td>26.51</td>
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<td>12.26</td>
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<td>32.73</td>
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<tr>
<td>0.85</td>
<td>38.16</td>
<td>1241.03</td>
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<tr>
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<td>41.72</td>
<td>1529.61</td>
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</tr>
<tr>
<td>1</td>
<td>43.42</td>
<td>1680.36</td>
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</tr>
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</table>
Chapter 8

CONCLUSION

In this work, an attempt has been made to study the Load flow and the transient stability of the multi-machine system using FACT Devices. The Load flow studies are carried out with and without STATCOM and Newton-Raphson method is used in Load flow. The results indicated an overall improvement network voltage profile. And in general more reactive Power was available in the network with STATCOM installed than without and the generator\textsuperscript{2} increases its share of reactive power absorption when compared with the base case.

In Transient stability study the step-by-step methods are used and the results have been simulated using MATLAB. The classical study has been carried out on the same five bus power system constituting two generators, a STATCOM and four loads. Modified Euler’s method has been applied to the solution of the differential equations in transient stability studies. The results have been tabulated and corresponding swing curves are plotted.

From the Stability study, we can conclude that if the fault is cleared in 0.15 sec during a study period of 1.0 sec, the system is found to be in stable condition, and if the fault clearing time is 0.2 sec the system is found to be in unstable condition. The transient stability can be further increased by temporarily increasing the voltage above the
regulation reference for the duration of the first acceleration of the machine. The voltage increased above its nominal value will increase the electric power transmitted and thus, will also increase the deceleration of the machine and thereby there will be an attainable increase in transient stability margin when compared to a system without STATCOM. The results of this book are compared with the results from G.W.Stagg and A.H.E.L – abiad “Computer Methods in power systems” and can significantly point that the stability increased by 0.05secs with Installation of STATCOM in the system. This proves that STATCOM improves the transient stability of a System.
Appendix A

Fig A.1 Single line diagram representation of 5 bus system for transient stability calculation

System data

A.1: 5-Bus system data

Number of buses: 5
Number of generators: 2
Number of lines: 7
Number of tap changing transformers: 0
Slack bus number: 1
Number of shunts: 0
Base in MVA: 100
Convergence factor: 0.0001
Acceleration factor: 1.4

Table A.1: Impedance and line charging admittance for a 5-Bus system

<table>
<thead>
<tr>
<th>Starting bus</th>
<th>Ending bus</th>
<th>Impedance</th>
<th>Line charging Admittance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>0.02</td>
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<tr>
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<td>0.0</td>
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<tr>
<td>2</td>
<td>3</td>
<td>0.06</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>0.06</td>
<td>0.0</td>
</tr>
<tr>
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<tr>
<td>4</td>
<td>5</td>
<td>0.08</td>
<td>0.0</td>
</tr>
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</table>
Table A.2: Scheduled generation and loads and specified bus voltages for a 5-Bus system

<table>
<thead>
<tr>
<th>Bus number</th>
<th>Generation</th>
<th>Load</th>
<th>Bus voltages</th>
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<td>MVAR</td>
<td>MW</td>
</tr>
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<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
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<td>30.00</td>
<td>20.00</td>
</tr>
<tr>
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<td>0.00</td>
<td>0.00</td>
<td>45.00</td>
</tr>
<tr>
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</tr>
<tr>
<td>5</td>
<td>0.00</td>
<td>0.00</td>
<td>60.00</td>
</tr>
</tbody>
</table>

Table A.3: Inertia constants, direct axis transient reactance

<table>
<thead>
<tr>
<th>M/C number</th>
<th>Inertia constant</th>
<th>Direct axis transient reactance</th>
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</thead>
<tbody>
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<td></td>
<td>H</td>
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</tr>
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<td>50.0</td>
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</table>
Table A.4: Static Synchronous Compensator Data (STATCOM)

<table>
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<th>Values in (p.u)</th>
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<tr>
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<tr>
<td>Target Active power Flow</td>
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<tr>
<td>Target Reactive Power Flow</td>
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<tr>
<td>Initial Source Voltage</td>
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</tr>
<tr>
<td>Initial Source Angle</td>
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</tr>
<tr>
<td>Lower limit of Voltage magnitude</td>
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</tr>
<tr>
<td>Upper limit of Voltage Magnitude</td>
<td>0.9</td>
</tr>
</tbody>
</table>


[29] Dussan povh Siemens AG “Modeling of FACTS in Power system Studies” IEEE

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[33] Tariq MASOOD.ch, Dr. Abdel-Aty Edris.Pro. Dr. RK Aggarwal “Static synchronous Compensator (STATCOM) modeling and analysis Techniques by Matlab & SAT/FAT Acceptance tests in the light of Commisioning & Installation Scenarios.” PSC 2006

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