Power Flow Study and Analysis using STATCOM

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***Abstract*— STATCOM is Flexible AC Transmission System (FACTS) device which can be used to maintain the voltage profile at the bus in the power system. This paper has discussed the STATCOM operation and it's V-I characteristics. In this paper the power flow is calculated with STATCOM with the help of iterative Newton-Raphson method. Six bus system is considered to validate the results obtained and they are presented with and without use of STATCOM in the system.**

***Index Terms*—STATCOM, FACTS, Newton-Raphson method**

I. INTRODUCTION

The increasing demand of electricity with high power quality along with more reliable and secure power system is fulfilled by providing the electricity which operates more flexibly and with best utilization. This increase in demand can be fulfilled either by installing new transmission lines or by increasing power transfer capability of the transmission line. The effective and economical solution is to increase transfer capability of transmission line giving attention to more utilization. To operate the power system flexibly, controlling action should be made fast by utilizing the advance research and development in power electronics technology. Initially the power system is controlled mechanically. Further, the power transmission capacity has been enhanced without exceeding the thermal limit of transmission line and is achieved by incorporating **F**lexible **AC** **T**ransmission **S**ystem (FACTS) technology [1][3].

With the use of FACTS technology, the parameters of the power system such as shunt impedance, series impedance including current, voltage and phase angle are controlled. Previously capacitor banks are used to control the voltage and reactive power. However, the FACTS technology consists of collection of various types of controllers and these can be applied to the power system individually or in the combination to control the parameters. The FACTS technology uses the basic elements of power electronics such as Thyristors. Besides, the FACTS controller is chosen according to the applications to overcome the defined problem. [1][2][3].

The compensator has two effects which appeared immediately. The first is it alters no load supply point voltage and second is it modifies sensitivity of supply point voltage to load reactive power. There are two types of compensators, active and passive compensators. Normally the passive compensators include the devices which are permanently connected for step less variation of reactive power. Generally shunt devices are included in active compensators. These compensators maintain constant voltage at the bus terminals to which they are connected.

Basically there are four types of FACTS controllers:
A] Shunt controller
B] Series Controller
C] Shunt-Series Controller
D] Series-Series Controller

The series controller injects the voltage in series with the transmission line with any phase angle according to driving voltage to control the line current. The shunt controller draws or injects the current into the power system. The combination of shunt and series controller could inject the current via shunt controller of the system and injects the voltage via series controller of the system. These are coordinately control. The combined Series-Series controller provides independent reactive power compensation with the transmission of real power via DC link. In multiline transmission system these types of controller are used which controlled coordinately. The list of all controllers is given in Table I.

Considering simple two machine system shown in Fig.1, the power flow equation is given by,

$$P = \frac{E * V}{X} \sin \delta \qquad (1)$$

Where,
E is the sending end voltage
V is receiving end voltage

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X is the impedance of transmission line

is the power angle

TABLE I. LIST OF FACTS CONTROLLER

Types of FACTS Controllers	**Sub-classes of FACTS Controllers**
Shunt Controller	1. Static Synchronous Compensator (STATCOM) 2. Static Synchronous Generator (SSG) 3. Battery Energy Storage System (BESS) 4. Thyristor Controlled Reactor (TCR) 5. Thyristor Switched Reactor (TSR) 6. Thyristor Switched Capacitor (TSC)
Series Controller	1. Static Synchronous Series Compensator (SSSC) 2. Thyristor Controlled Series Capacitor (TCSC) 3. Thyristor Switched Series Capacitor (TSSC) 4. Thyristor Controlled Series Reactor (TCSR)
Combined Series-Series Controller	1. Interline Power Flow Controller (IPFC)
Combined Shunt-Series Controller	1. Unified Power Flow Controller (UPFC) 2. Thyristor Controlled Phase Shifting Transformer (TCPST)

From Equation 1 it is clear that the power flow depends on transmission angle between sending end and receiving end voltage as shown in Fig.1

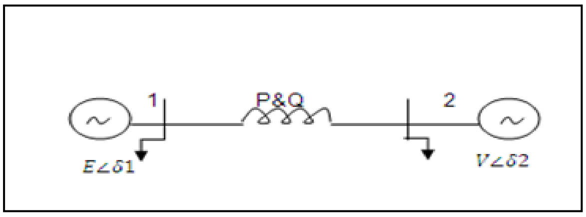

Fig.1 Simple two machine system [1]

From Equation 1 it is seen that the maximum power will be transferring when reaches to 90^0. This power flow can be controlled by varying the voltage magnitude E and V respectively. This change of magnitude affects on angle, which leads to change in flow of reactive power. The power flow can also be controlled by injecting the voltage in series with line [1]. If this injected voltage is quadrature then it directly affects flow of line current. Hence the active power flow changes [4].

This paper is divided into five sections. Section I deals with introduction of FACTS devices whereas Section II discusses the operation and characteristics of STATCOM. Section III describes the application of Newton-Raphson method to load flow studies. Example and results are discussed in Section IV. The conclusions of the work are highlighted in Section V.

II. STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

The STATCOM consist of SCRs, IGBTs, GTOs, etc. When synchronous machine is over excited it provides positive VARS behaving as capacitor and when the machine is under excited, it provide negative VARS and it behaves as inductor. STATCOM is a shunt connected device which is a DC to AC converter. Fig.2 shows the shunt compensator where V_{ta}, V_{tb} and V_{tc} are the terminal voltages [1].

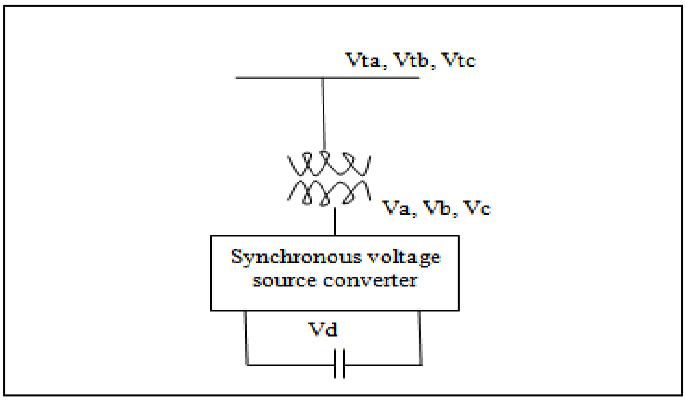

Fig.2 Shunt Compensator

The STATCOM consist of three phase step down transformer, three phase converter and capacitor. The converter can control the magnitude and angle of the corresponding AC voltages. The reactive power flow depending on the magnitude of voltage and the real power flow, depend on the angle which is either lagging or leading. Here when current flowing through STATCOM is leads by 90° of other side, then it acts as inductor. When current lags by 90° of other side, then it acts as capacitor. The value of the capacitor should be properly chosen so that it can provide sufficient reactive power. Fig.3 shows the V-I characteristics of STATCOM [1][5][6].

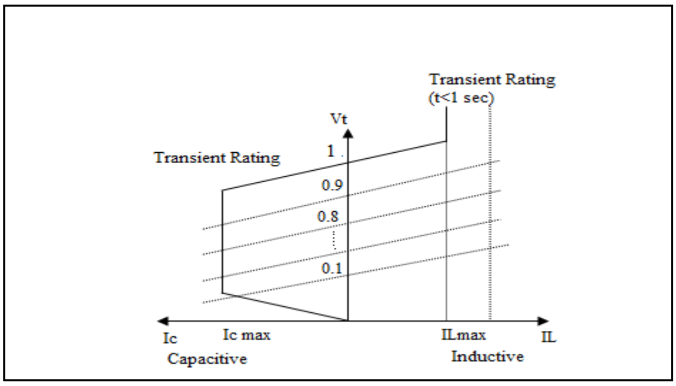

Fig.3 V-I characteristics of STATCOM [1]

From V-I characteristics, it is seen that STATCOM can also operate at the low voltage maintaining the maximum current independent of the voltage [7].

III. APPLICATION OF NEWTON-RAPHSON METHOD TO POWER FLOW STUDY

The power in transmission line which is consumed by the load is calculated by using iterative technique which is commonly referred as power flow solution [8][9]. There are different methods to obtain the solution.

1. Gauss Seidel Method
2. Newton-Raphson Method
3. Decoupled Method
4. Fast decoupled Method

Each method has its own advantages and disadvantages. Generally for accuracy point of view, Newton-Raphson method is preferred. The computation time required for each iteration is somewhat more but less iteration are required [3]. The static load flow equations are given by,

$$P_i = \sum_{j=1}^{n} V_i V_j Y_{ij} \cos\left(\theta_{ij} + \delta_j - \delta_i\right) \qquad (2)$$

$$Q_i = -\sum_{j=1}^{n} V_i V_j Y_{ij} \sin\left(\theta_{ij} + \delta_j - \delta_i\right) \qquad (3)$$

These Equations 2 and 3 are used to calculate real and reactive power. Consider three bus systems which consist of SLACK, PQ, PV buses. According to the type of bus corresponding quantities are specified. To apply Newton-Raphson method, initially power mismatch have to be calculated as shown in Equations 4 and 5 [9][10].

$$\Delta P_i = P_{i\,Speci} - P_{i\,calcu} \qquad (4)$$

$$\Delta Q_i = Q_{i\,Speci} - Q_{i\,calcu} \qquad (5)$$

In case of PQ bus, the real and reactive powers are known quantities and for PV bus, only real power is known. By combining all these equations with separation of known and unknown quantities in matrix form, we write as shown in Equation 6,

$$\begin{bmatrix} \Delta P_2 \\ \Delta P_3 \\ \Delta Q_2 \end{bmatrix} = \overset{\textbf{H} \qquad\qquad \textbf{N}}{\underset{\textbf{J} \qquad\qquad \textbf{L}}{\begin{bmatrix} \left(\frac{\partial P_2}{\partial \delta_2}\right)_{\delta_2^0} & \left(\frac{\partial P_2}{\partial \delta_3}\right)_{\delta_3^0} & \left(\frac{\partial P_2}{\partial |V_2|}\right)_{|V|_2^0} \\ \left(\frac{\partial P_3}{\partial \delta_2}\right)_{\delta_2^0} & \left(\frac{\partial P_3}{\partial \delta_3}\right)_{\delta_3^0} & \left(\frac{\partial P_3}{\partial |V_2|}\right)_{|V|_2^0} \\ \left(\frac{\partial Q_2}{\partial \delta_2}\right)_{\delta_2^0} & \left(\frac{\partial Q_2}{\partial \delta_3}\right)_{\delta_3^0} & \left(\frac{\partial Q_2}{\partial |V_2|}\right)_{|V|_2^0} \end{bmatrix}}} \begin{bmatrix} \Delta \delta_2 \\ \Delta \delta_3 \\ \Delta |V_2| \end{bmatrix}$$

Equation 6 consists of the matrix with partial derivatives which is known as Jacobian matrix. This matrix is divided in to four sub matrices such as H, N, J and L.

Where,

$H =, \quad N =, \quad J =, \quad L =$

This matrix can also be written as shown in Equation 7

$$J = \begin{bmatrix} H_{22} & H_{23} & N_{22} \\ H_{32} & H_{33} & N_{32} \\ J_{22} & J_{23} & L_{22} \end{bmatrix}$$

This is the procedure to solve the Newton-Raphson method. With the addition of STATCOM to any one of the bus, the power flow equation at that bus is written as shown in Equations 8 and 9. These equations shows the active and reactive power injected or absorbed by STATCOM. The equivalent circuit of STATCOM is shown in Fig.4.

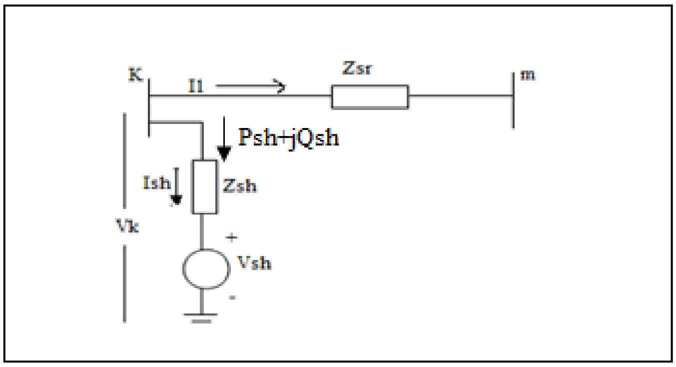

Fig.4 STATCOM connected to bus

$$P_{sh} = V_k^2 G_{sh} + V_{sh} V_k \left(G_{sh} \cos(\theta_k - \theta_{sh}) + B_{sh} \sin(\theta_k - \theta_{sh})\right)$$

$$Q_{sh} = -V_k^2 B_{sh} + V_{sh} V_k \left(G_{sh} \sin(\theta_k - \theta_{sh}) - B_{sh} \cos(\theta_k - \theta_{sh})\right)$$

With the use of Equations 8 and 9, powers at the buses are calculated where STATCOM is connected. The steps of execution of program are given below.

1. Initial reading of given data viz. system bus types, voltages, angles, real power, reactive power, line data etc. which is stored in files.
2. Initially flat voltage profile is considered.
3. Y bus is calculated in the polar form.
4. According to bus data, power mismatches are calculated.
5. Further Jacobian matrix elements are calculated using Equations 2 and 3.
6. Every bus is to be checked to know location of STATCOM.
7. According to location of STATCOM, voltage at that bus is calculated with a tolerance level of $1e^{-7}$.

IV. EXAMPLE AND RESULT

Six bus system is shown in Fig.5 with generator at buses 1, 2 and 3. The line data and bus data are given in appendix [11].

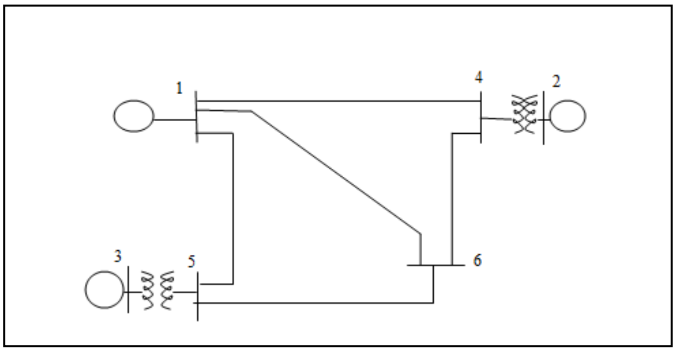

Fig.5 Six bus system without STATCOM

The above example is initially solved without insertion of STATCOM. The voltages at each bus are calculated. The results are shown in Table II.

TABLE II. RESULTS OF BUS VOLTAGES AND ANGLE WITHOUT STATCOM

Bus number	Voltage (pu)	Angle (radian)
1	1.0600	0.0000
2	1.0400	1.4700
3	1.0300	0.8004
4	1.0077	-1.4014
5	1.0163	-1.4991
6	0.9410	-5.6070

The results show the voltage at each bus and its corresponding angle. The convergence has been obtained with in 4 iterations during execution of Newton-Raphson method. Six bus system with STATCOM connected at bus 5 is shown in Fig.6. If the STATCOM is connected to bus 5, then that bus is converted to PV bus where the voltage is fixed to certain value. The corresponding results are shown in Table III.

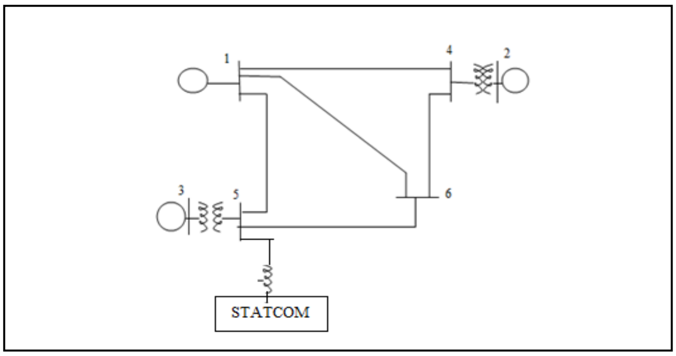

Fig.6 Six bus system with STATCOM

TABLE III. RESULTS WITH STACOM CONNECTED TO BUS 5

Bus number	Voltage (pu)	Angle (radian)
1	1.0600	0.0000
2	1.0400	1.4592
3	1.0300	1.0099
4	1.0065	-1.4157
5	1.0000	-1.3270
6	0.9848	-5.6019

From the results, it is seen that when the STATCOM is not connected, bus 5 shows over voltage. If STATCOM is connected to bus 5, it maintains the voltage by absorbing reactive power [12]. Hence, by introducing the STATCOM to the bus, the overall power quality is improved. The results obtained above has been analyzed by executing the computer programme in Simulation software [13][14]. However, it is observed that the effectiveness of the behavior of the STATCOM device with changes in generation and/or load is generally analyzed with large bus system.

V. CONCLUSIONS

STATCOM is FACTS device used to maintain the bus voltage at designated bus of the transmission line. The performance of STATCOM is studied and analyzed with six bus system which shows the absorption of reactive power when connected to bus number 5. With the use of the FACTS device, the effective control of the power system is achieved.

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APPENDIX

Bus Data:

Bus	Type	Vsp	Theta	PGi	QGi	PLi	QLi	Qmin	Qmax
1	1	1.06	0	0	0	0	0	0	0
2	2	1.04	0	150	0	0	0	0	140
3	2	1.03	0	100	0	0	0	0	90
4	3	1.0	0	0	0	100	70	0	0
5	3	1.0	0	0	0	90	30	0	0
6	3	1.0	0	0	0	160	110	0	0

Line data:

From Bus	To Bus	R	X	B/2	Transformer Tap
1	4	0.035	0.225	0.0065	1
1	5	0.025	0.105	0.0045	1
1	6	0.040	0.215	0.0055	1
2	4	0.000	0.035	0.0000	1
3	5	0.000	0.042	0.0000	1
4	6	0.028	0.125	0.0035	1
5	6	0.040	0.175	0.0300	1