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Use of FACTS Controller for Relieving Congestion in Power System

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***Abstract:** Congestion in the transmission lines is one of the technical problems that appear particularly in the deregulated environment. There are two types of congestion management methodologies to relieve it. One is non-cost free methods and another is cost-free methods, among them later method relieves the congestion technically whereas the former is related with the economics. In this paper congestion is relieved using cost free methods. Using FACTS devices, congestion can be reduced without disturbing the economic matters. STATCOM and UPFC are two mainly emerging FACTS devices and they are used in this paper to reduce the congestion. Above method is tested on 5-bus system and it can be extended to any practical system. FACTS devices can be an alternative to reduce the flows in heavily loaded lines, resulting in an increased power capability, low system loss, improved stability of the network, by controlling the power flows in the network. Modeling, simulation and analysis of 5 bus system in MATLAB environment is proposed in this paper. Comparison with and without FACTS devices is done to control the power flow and obtain the power system steady state operation. The same system is again analyzed under dynamic conditions and the performance of these devices is observed.*
***Keywords:** FACTS, UPFC, STATCOM*

I. INTRODUCTION

Growth in load demand and the push to change the generation sources to smaller plant utilizing renewable energy sources along with uncertainty of transaction is likely to strain existing power system. This will lead to transmission system functioning closer to their operating limits and caused increased congestion .Therefore ensuring the transmission system is flexible enough to meet new and less predictable power supply and demand condition in competitive electricity market will be a real challenge. In India the power sector was mainly under the government ownership (>95% distribution and ~98% generation) under various states and centaral government utilities, till 1991. The remarkable growth of physical infrastructure was facilitated by four main policies: 1) centralized supply and grid expansion 2) large support from government budgets, 3) development of sector based on indigenous resources.

In mid 1990's Orissa began a process of fundamental restructuring and deregulation of the state power sector. Thereby effective means for congestion management has become an increasingly important issue, especially for deregulated system. New enabling technologies that can maintain the stability and reliability of power system while handling large volume of transmission are able to provide solution .One example of such technology is the Flexible AC Transmission Sysytem .The ability of FACTS controller to support and control power flows in system networks is well known [1-3]. And it is anticipated that the application of FACTS controller will grow in future power system.

The UPFC and STATCOM are the example of second and third generation type of FACTS controller, based on power electronics switches. UPFC has the advantage of controlling both active and reactive power flow simultaneously over STATCOM. The first aspect is the flexible power system operation according to the power flow control capability of FACTS devices. The other aspect is the improvement of transient and steady-state stability of power systems. FACTS devices are the right equipment to meet these challenges [7].

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II. FLEXIBLE AC TRANSMISSION SYSTEM

Flexible AC Transmission System (Facts) is a new integrated concept based on power electronic switching converters and dynamic controllers to enhance the system utilization and power transfer capacity as well as the stability, security, reliability and power quality of AC system interconnections.

III. UPFC STRUCTURE, OPERATION AND CONTROL

Two main blocks of UPFC are Shunt inverter and series inverter.

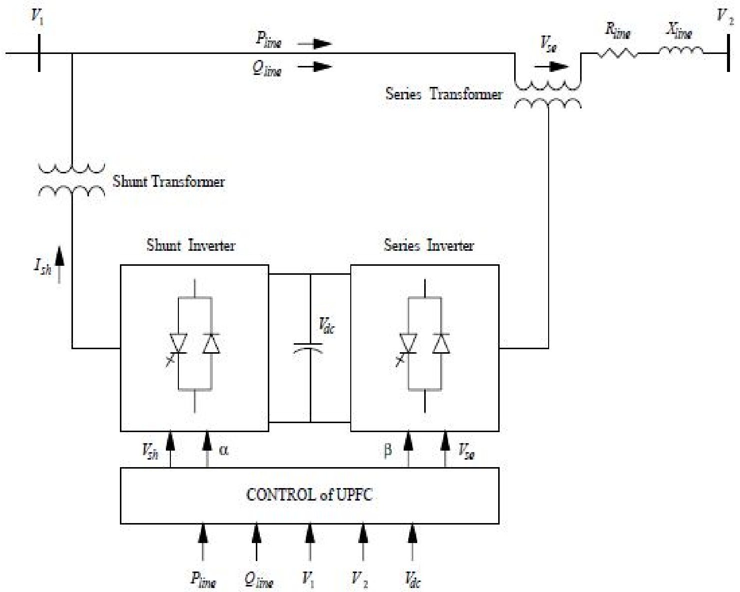

Fig 1: Block diagram of UPFC

A. Shunt Inverter

The shunt inverter is operated in such a way as to draw a controlled current from the line. One component of this current is automatically determined by the requirement to balance the real power of the series inverter. The remaining current component is reactive and can be set to any desired reference level (inductive or capacitive) within the capability of the inverter.[1]

B. Series Inverter

The series inverter controls the magnitude and angle of the voltage injected in series with the line. This voltage injection is always intended to influence the flow of power on the line; its working is similar to that of SSSC.

IV. STATCOM: STRUCTURE, OPERATION AND CONTROL

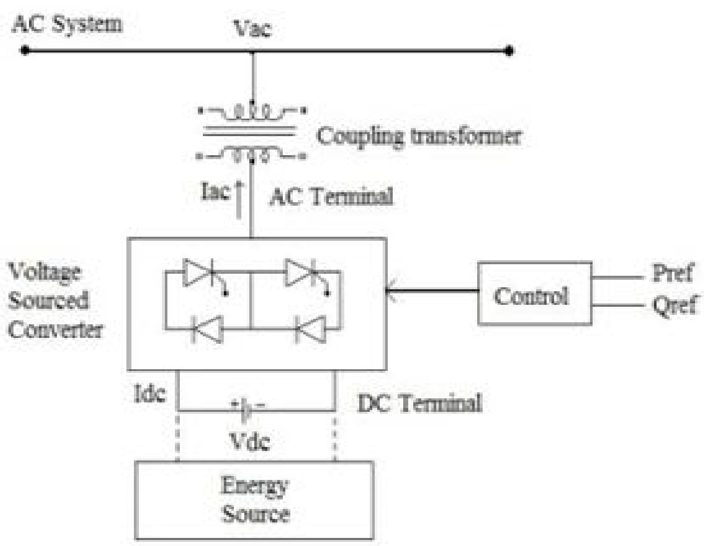

Fig2: Block diagram of STATCOM

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The STATCOM is a shunt connected device. It is connected to the system through a coupling transformer. The control is obtained by the reference values of active (Pref) and reactive power (Qref) . [9, 12]The basic principle for a STATCOM is explained with the help of figure3. The output voltage of the GTO converter (V i) is controlled in phase with the system voltage (V s), as shown in this figure 3, the output current of the STATCOM (I) varies depending on (V i). If Vi is equal to Vs, then no reactive power is delivered to the power system. If Vi > Vs, leading reactive power flows from the STATCOM (Capacitive mode). If V i < Vs, hence lagging reactive power flows into the STATCOM (inductive mode). The amount of reactive power is proportional to the difference between Vs and Vi. This is also the same basic operating principle as a rotating synchronous condenser. Working and V – I characteristics is shown in figure 3[7]. If the system exceeds a low voltage (V1) or high voltage limit (V2), the STATCOM acts as a constant current source by controlling the converter voltage Vi appropriately.
Thus ,when operating at its voltage limits , the amount of reactive power compensation provided by STATCOM is more than most common competing FACTS controllers namely Static Var Compensator (SVC). There by making reactive power controllability of the STATCOM superior to that of SVC, particularly during times of system distress.

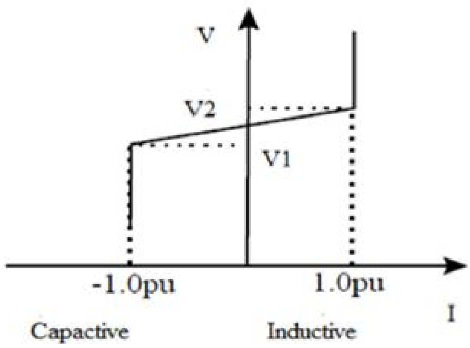

Fig 3: working of STATCOM

V. POWER FLOW MODEL OF UPFC:

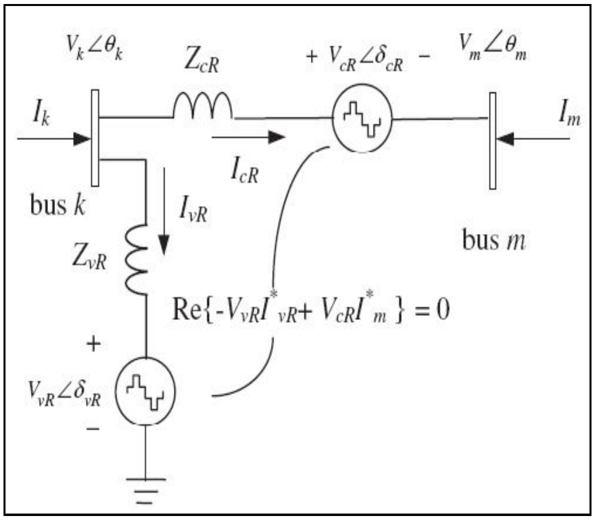

Fig 4: Equivalent circuit of UPFC

The equivalent circuit consists of two coordinated synchronous voltage sources should represent the UPFC adequately for the purpose of fundamental frequency steady state analysis [1]. Such an equivalent circuit is shown in Fig 4.
The UPFC voltage sources are:

$$E_{vR} = V_{vR}(\cos\delta_{vR} + j\sin\delta_{vR}) \qquad \text{.....1}$$

$$E_{cR} = V_{cR}(\cos\delta_{cR} + j\sin\delta_{cR}) \qquad \text{.......2}$$

where V_{vR} and δ_{vR} are the controllable magnitude ($V_{vRmin} \leq V_{vR} \leq V_{vRmax}$) and phase angle ($0 \leq \delta_{vR} \leq 2\pi$) of the voltagesource representing the shunt converter. The magnitude $V_{cR}$and phase angle δcR of the voltage source representing the series converter are controlled between limits ($V_{cRmin} \leq V_{cR} \leq V_{cRmax}$) and ($0 \leq \delta_{cR} \leq 2\pi$), respectively. The phase angle ofthe series injected voltage determines the mode of power flow control [1], [4]. If δ_{cR} is in phase with the nodal voltage angle Θk, the UPFC regulates the terminal voltage. If δ_{cR} is in quadrature with Θ_k, it controls active power flow, acting as aphase shifter. If δ_{cR} is in quadrature with line current angle then it controls active power flow, acting as a variable series compensator. At any other value of δ_{cR}, the UPFC operates as a combination of voltage regulator, variable series compensator, and phase shifter. The magnitude of the series injected voltage determines the amount of power flow to be controlled .Based on the equivalent circuit shown in Fig 4 the active and reactive power equations are,

At bus k:

$$P_k = V_k^2 G_{kk} + V_k V_m [G_{km} \cos(\theta_k - \theta_m) + B_{km} \sin(\theta_k - \theta_m)] + V_k V_{cR} [G_{km} \cos(\theta_k - \delta_{cR}) + B_{km} \sin(\theta_k - \delta_{cR})] + V_k V_{vR} [G_{vR} \cos(\theta_k - \delta_{vR}) + B_{vR} \sin(\theta_k - \delta_{vR})]$$

$$Q_k = -V_k^2 B_{kk} + V_k V_m [G_{km} \sin(\theta_k - \theta_m) - B_{km} \cos(\theta_k - \theta_m)] + V_k V_{cR} [G_{km} \sin(\theta_k - \delta_{cR}) - B_{km} \cos(\theta_k - \delta_{cR})] + V_k V_{vR} [G_{vR} \sin(\theta_k - \delta_{vR}) - B_{vR} \cos(\theta_k - \delta_{vR})]$$

At bus m:

$$P_m = V_m^2 G_{mm} + V_m V_k [G_{mk} \cos(\theta_m - \theta_k) + B_{mk} \sin(\theta_m - \theta_k)] + V_m V_{cR} [G_{mm} \cos(\theta_m - \delta_{cR}) + B_{mm} \sin(\theta_m - \delta_{cR})]$$

$$Q_m = -V_m^2 B_{mm} + V_m V_k [G_{mk} \sin(\theta_m - \theta_k) - B_{mk} \cos(\theta_m - \theta_k)] + V_m V_{cR} [G_{mm} \sin(\theta_m - \delta_{cR}) - B_{mm} \cos(\theta_m - \delta_{cR})]$$

A. Equations For Series Converter

$$P_{cR} = V_{cR}^2 G_{mm} + V_{cR} V_k [G_{km} \cos(\delta_{cR} - \theta_k) + B_{km} \sin(\delta_{cR} - \theta_k)] + V_{cR} V_m [G_{mm} \cos(\delta_{cR} - \theta_m) + B_{mm} \sin(\delta_{cR} - \theta_m)]$$

$$Q_{cR} = -V_{cR}^2 B_{mm} + V_{cR} V_k [G_{km} \sin(\delta_{cR} - \theta_k) - B_{km} \cos(\delta_{cR} - \theta_k)] + V_{cR} V_m [G_{mm} \sin(\delta_{cR} - \theta_m) - B_{mm} \cos(\delta_{cR} - \theta_m)]$$

B. Equations For Shunt Converter

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

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

Assuming lossless converter values, the active power supplied to the shunt converter, P_{vR}, equals the active power demanded by the series converter, P_{cR}; i.e. $P_{vr+} P_{cr} = 0$. Furthermore, if the coupling transformers are assumed to contain no resistance then the active power at bus k matches the active power at bus m. Accordingly, . $P_{vr} + P_{cr}$ = Pk +Pm= 0. The UPFC power equations are combined with those of the AC network.

VI. POWER FLOW MODEL OF STATCOM

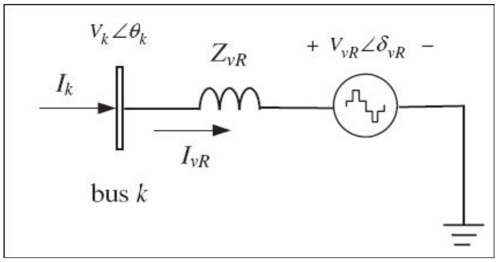

Fig 5:Equivalent circuit of STATCOM

The Static synchronous compensator (STATCOM) is represented by a synchronous voltage source with minimum and maximum voltage magnitude limits [12]. The bus at which STATCOM is connected is represented as a PV bus, which may change to a PQ bus in the events of limits being violated. In such case, the generated or absorbed reactive power would correspond to the violated limit. The power flow equations for the STATCOM are derived below from the first principles and assuming the following voltage source representation [2].

$$E_{vR} = V_{vR}(\cos\delta_{vR} + j\sin\delta_{vR})$$

$$S_{vR} = V_{vR}I_{vR}^* = V_{vR}Y_{vR}^*(V_{vR}^* - V_k^*)$$

The following are the active and reactive power equations for the converter at bus k,

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

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

And,

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

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

Based on the power flow models given above for STATCOM and UPFC the analysis simulation and modeling of the system is done.

VII. STATIC ANALYSIS OF THE SYSTEM

The objectives of this Paper are to:

1) Simulate 5 bus power system network using MATLAB software .
2) Model UPFC and STATCOM in5 bus power system network and determine the power flow .
3) Perform the steady-state analysis of the 5 bus power system network before and after UPFC and STATCOM are applied.

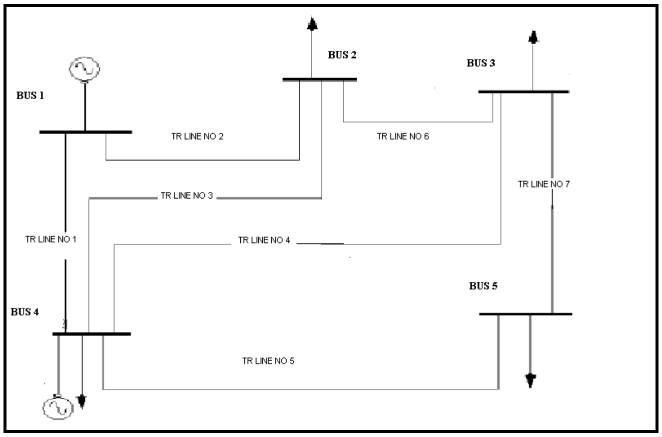

Table 1: Bus results with and without FACTS devices

BUS NO.	Without FACTS DEVICES(pu)	WITH STATCOM	WITH UPFC
1	1.06	1.06	1.06
2	0.9871	1.013	0.9998
3	0.9836	0.9946	0.9901
4	1.01	1.002	1.0037
5	0.9721	0.9753	0.9746

Table 2: Line result without FACTS devices

LINE NO	P (p.u)	Q(p.u)
01	0.1340	1.2118
02	0.1522	0.2122
03	-2.2139	0.5220
04	-2.1820	0.3555
05	-6.2785	2.9302
06	-22.9455	10.9021
07	-3.5902	5.5066

The simulation yields the power flow for lines and bus active and reactive powers which are tabulated above .From the power flow results for the 5-bus system, it can be observed that the voltage magnitudes at bus 2, bus 3 and bus 5 are lower than 1.0 p.u.So , these are the potential buses where FACTS devices can be included .The active power in line 6 is 22.9455 p.u and the reactive power is 10.9021 p.u .

Table 3: Line result with STATCOM at bus 2

LINE NO	P (p.u)	Q(p.u)
01	1.4068	0.8461
02	0.1492	0.2457
03	5.3052	5.6402
04	5.3496	5.3818
05	7.8564	7.2254
06	30.6750	30.9922
07	-3.6099	5.3440

It is very clear from the comparison of table 2 and table 3,that the nodal voltage is maintained at 1.013 at bus 2 by STATCOM and the phase angle is also improved to -4.7529(degrees) from 0.464(degrees) . The active power is also increased from 22.9455 (p.u) to 30.6750 (p.u)

The installation of the STATCOM resulted in improved network voltage profile (Table 4.3).The slack generator reduces its reactive power generation by 5.9% compared with the base case .The reactive power absorbed by the bus 4 generator increased by 25% of the base case. In general, more reactive power is available in the network when compared with the base case due to the installation of STATCOM.

Table 4: Line result with UPFC at bus 2

Line no.	P	Q
01	0.2719	1.0112
02	0.3028	0.2468
03	-4.0745	2.0098
04	-4.0005	1.8088
05	-7.5400	9.9569
06	-30.1488	35.7096
07	2.7342	6.7163

UPFC increases the amount of reactive power supplied at the bus 2 to 35.7096 (p.u) which very high as compared to 30.9922 (p.u) with STATCOM and10.9021 (p.u) without any FACTS devices. There is increase in the active power also due to the demand of the UPFC series converter.

VIII. DYNAMIC ANALYSIS OF THE SYSTEM

In this analysis load is taken as the time varying entity .Simulation results (graphical) are as shown below.

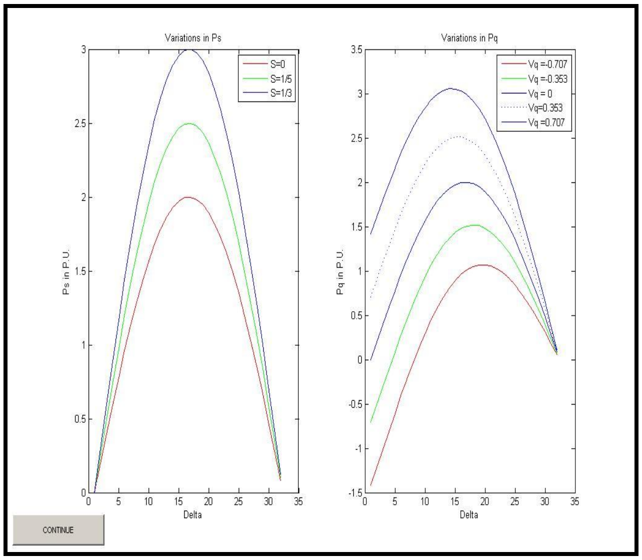

Fig 6: active power and reactive power variations with respect to phase angle δ.

Figure3 explains the importance of reactive power compensation at a load bus if there are no generators in the vicinity to regulate the bus voltage. The reactance factor (S = Xc/Xl) determines the nature of the active power curve. The higher the value of reactance factor the more is the value of active power. The various values of load bus voltages are shown in the figure and how this varies the reactive power along with the phase angle δ. Power reaches its maximum when Vq = 0.707. But instead of the FACTS devices if fixed capacitors are used for compensation then even if Vq is increased to 1.0 there is no change in the value of power which is not the case with SSC or UPFC. The Y- axis shows the Ps and Pq respectively inp.u and the X – axis shows the phase angle δ.

A. Power Flow Graphs With Statcom

The five bus system is dynamically analyzed with STATCOM at bus 2. Figure 4, below shows three results:

1) Voltage and current graphs
2) Phase distortion and current variations
3) Reactive power injected and phase injected.

The Y- axis shows the grespective parameters in p.u and the X - axis shows the time (in ms). Each result is further subdivided into three section, the first section (t=0 to t =480 ms) represents the system when the FACTS devices are not operating, the second section (t=500 to t=1000 ms) shows the active power compensation with STATCOM included and the third section (t=1000 to t= 1400ms) explains the reactive power compensation provided by the device in the system.

It can be clearly seen from the results obtained in figure 5.2 that the STATCOM provides far better compensation in terms of voltage , reactive power injected , current as compared to the base case when there are no devices in the system. The phase distortion is also reduced considerably .The STATCOM helps in maintaining the magnitude of current nearly the same in both the cases that is active as well as reactive power compensation

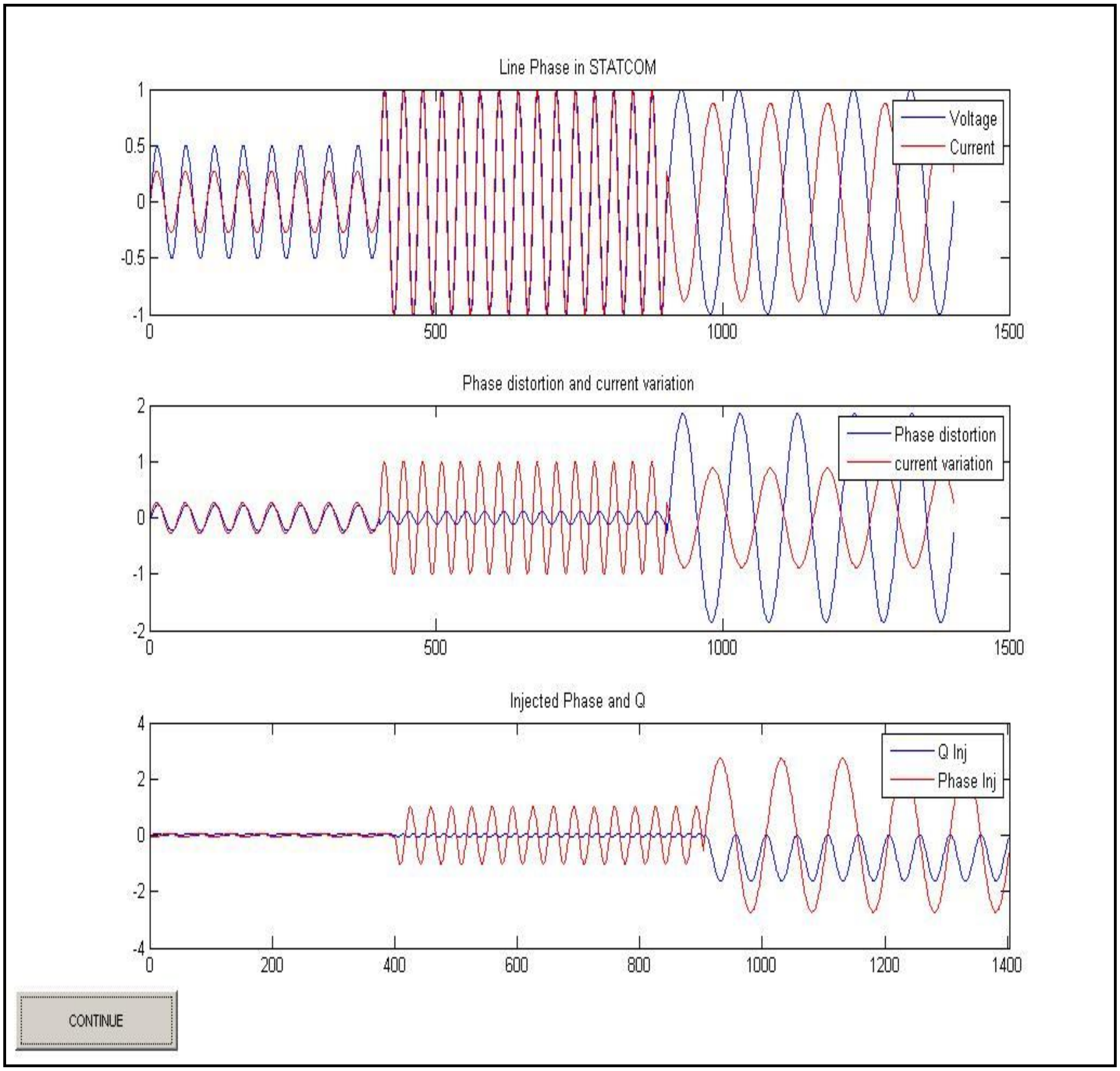

Fig 7: Graph showing the results of STATCOM inserted at bus 2

B. Power Flow Graphs With Upfc

The UPFC is included in bus 2 and bus 3.

Comparison of Figure 7 and 8 show that the system response with UPFC in the system is comparatively better that not only the base case but also the STATCOM results . The phase distortion has nearly become linear . This shows that UPFC can control not only voltage, impedance but also phase angle. All the three parameters are controlled by the UPFC and hence the name UNIFIED Power Flow Controller.

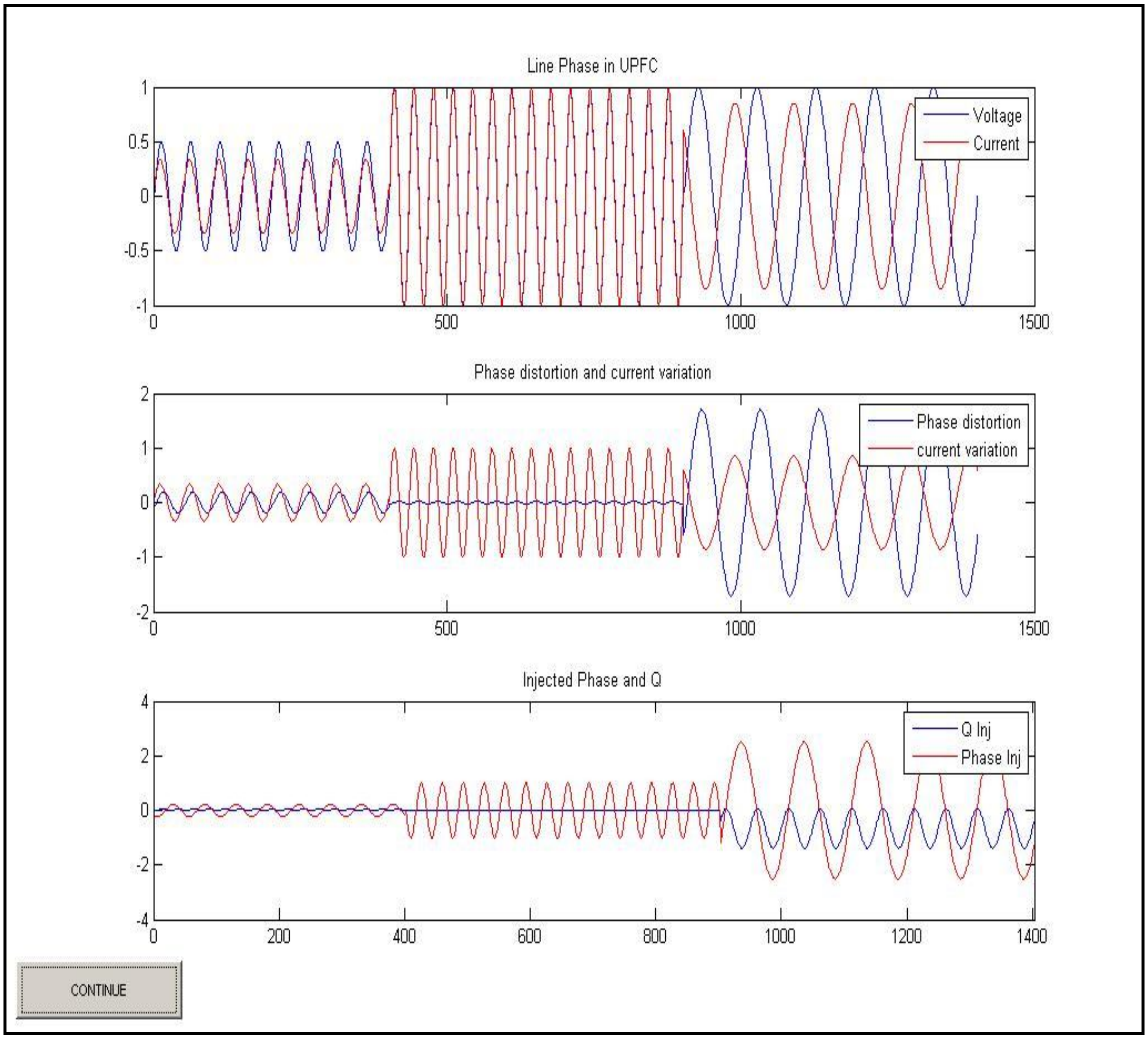

Fig 8: Graph showing the results of UPFC inserted at bus3 and 4

IX. CONCLUSION

This paper has proposed cost free congestion management methods required for smooth operation of deregulated power system. It gives the remedy for congestion by enhancing active power flow capability of transmission line. Simulation methods required for study of the steady state as well as dynamic operation of electrical systems with FACTS devices UPFC and STATCOM is analyzed in the paper. The power flow for the five bus system was analysed with and without FACTS devices. The power flow indicates that there is nearly 5.9 % increase in the reactive power absorption compared with the base case when STATCOM is included in bus 2. The largest reactive power flow takes place in the transmission line connecting bus 2 to bus 3, which is 30.9922 p.u. The direction of reactive power flow remains unchanged.

The sample 5 bus network is modified to include one UPFC to compensate the transmission line no. 6 linking bus 2 and bus 3. The UPFC shunt controller is set to regulate the nodal voltage magnitude at bus 2 at 1 p.u. There is large amount of increase in the active power as well as the reactive power. The steady state models of STATCOM and UPFC are analyzed and evaluated in Newton-Raphson algorithm.

Both, the static and the dynamic analysis show that UPFC is able to control not only the voltage but also the impedance and phase angle which affect the power flow in the transmission line. Same is true for the fourteen bus system also .Convergence is obtained in four iterations to a power mismatch tolerance of 10^{-12}. There is increase in the active power also due to the demand of the UPFC series converter. The negative sign shows the direction of power flow from the shunt converter end to the series converter end.

The STATCOM was able to effectively regulate the bus voltage magnitude at which it was connected but UPFC has proven to be far more better than the STATCOM for the system being analyzed .

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BIOGRAPHIES

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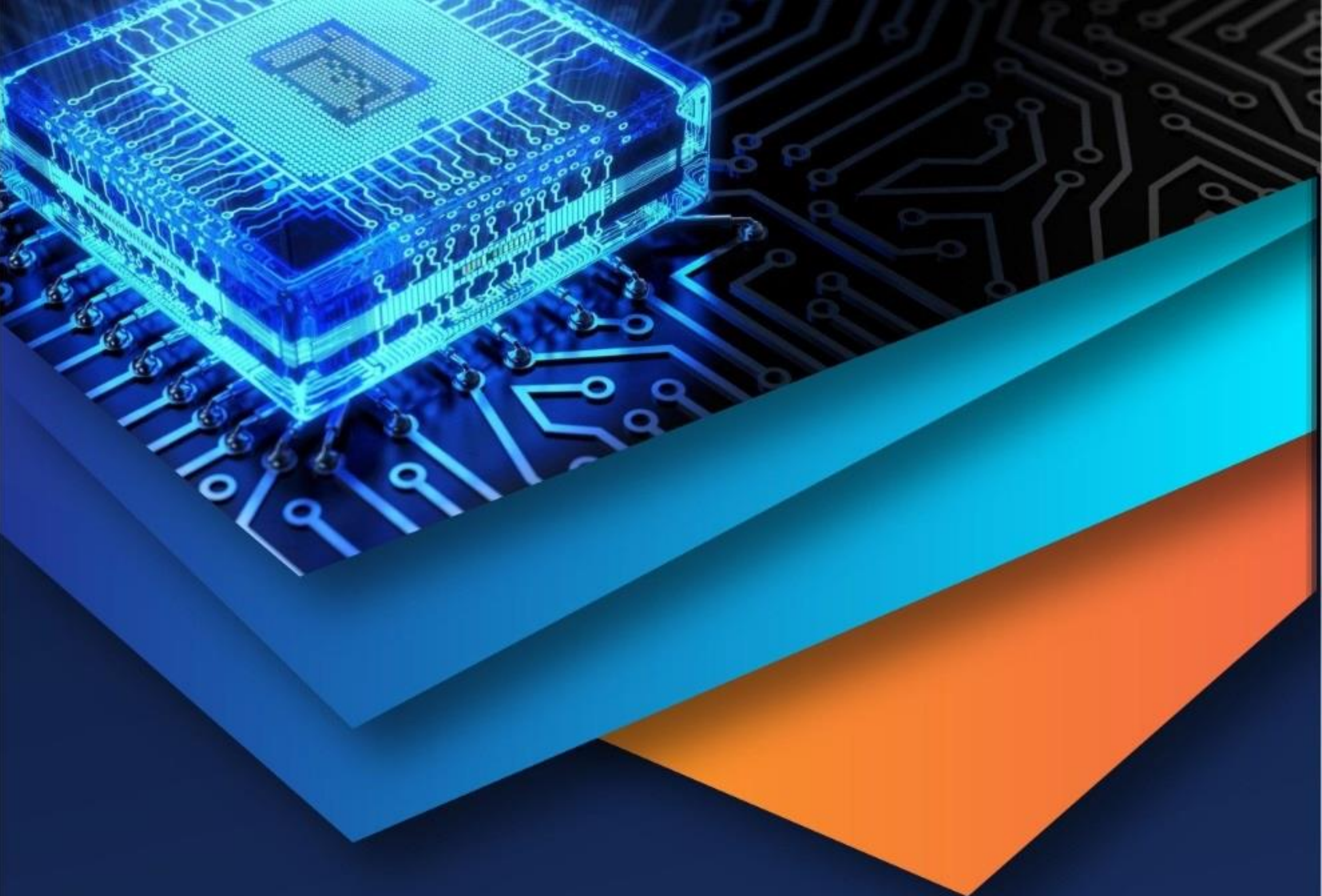

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