# Reactive power compensation in the Deregulating electrical power environment using FACT controllers applied to an Industrial Zone in India

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***Abstract*— In this paper, the reactive power requirement and the most suitable compensating FACT device for an industrial zone in the deregulating electrical power environment is investigated. The existing method of compensation are made of capacitors connected in series or shunt as bank, which is creating problems such as power quality issues and voltage instability. To overcome this problem FACT devices can be used as compensators. Though many compensating devices are actively present in the real time, in some places it is not yet developed completely. The FACT controllers are giving a very good solution for the reactive power compensation problem. A standard 16 bus system was taken from an industrial zone. Its real and reactive power requirement is calculated and the same is simulated for various FACT controllers such as SVC, STATCOM, UPFC, SSSC in MATLAB/Simulink environment. The best results are analysed and tabulated.**

***Index Terms*— deregulating electrical power,FACT controller,STATCOM,SVC,MATLAB.**

## 1. Introduction :

Nowadays, the most important problem that arises in the deregulating electrical power environment is reactive power compensation. In the deregulated electrical power environment, the entire power system is divided in to three major parts as Genco, Disco and Transco. Many private power producing sectors entered with renewable generator, non-renewable generators and distribution generators as competitors. The reactive power supplied by the generator and the transmission line is carried out using the relative electrical distance concept [1]**.** Circuit breakers are the frequently operated devices in the power grid due to that power quality problem will arises[2]. The reactive power management and control in the deregulated environment is discussed in [3-9] .The demand of power has doubled in the last decade everywhere. The constant increase in power flow has saturated the existing infrastructure. Distributed Energy Resources are constantly improving their reliability and power capabilities. Wind energy has proved to be a fastest growing renewable energy source globally and its large scale penetration in the interconnected systems is consistently imposing new challenges for the engineers. Attending to the technological advancements and the upgrading requirements of the power companies, a proper control scheme for the reactive power compensation in a wind farm is necessary.

The blackouts in August 14, 2003 in United States and Canada, August 28, 2003 in London, September 23, 2003 in Italy and May 25, 2005 in Moscow, Russia have left the world with great concerns over the nature of these blackouts, the main causes is improper reactive management.

The general voltage equation of a node is given by 1.1

$$V_i = V_i \cdot (\cos\phi_i + j \sin \phi_i) = V_i \angle \phi_i \qquad (1.1)$$

Real power generation limits: $P_g \min \leq P_g \leq P_g \max$
Reactive power generation limits: $Q_g \min \leq Q_g \leq Q_g \max$

The optimal power flow equation for real and reactive power flow is given by [5]

$$P_i = \sum_{k=1}^{N} |V_i|\,|V_k|\,(G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik}) \qquad (1.2)$$

$$Q_i = \sum_{k=1}^{N} |V_i|\,|V_k|\,(G_{ik} \sin\theta_{ik} - B_{ik} \cos\theta_{ik}) \qquad (1.3)$$

These theoretical equations can be used for real and reactive power calculations for any number of nodes.

The FACT devices can change the power system parameters and perform power flow control in a flexible manner and thus increasing transmission capacity, minimizing losses and improving power system stability [10]. Zones are formed by splitting a control area of an interconnected power system into autonomous voltage sub-areas with sufficient reactive power reserves, using the electrical distance method. First step of an optimization algorithm determines zonal reactive power prices based on generator cost functions for reactive power production [11]. The reactive power control of IEEE39 bus system was presented in [12]. The performance analysis of a sujino fuzzy logic based controller for the studied isolated hybrid power system model is carried out which tracks the degree of reactive power compensation in real time[13]. The reactive power planning problem has been studied using conventional mathematical programming techniques. More recently heuristics and mainly meta-heuristics such as simulated annealing, ant colony, PSO, Plant growth simulation algorithm, tabu searched and fuzzy based techniques and genetic algorithm have been used to deal with this VAR planning problem.[14 -19].

A complex combinatorial problem of locating and sizing capacitors for reactive power compensation in electric radial distribution networks has been modelled as a multi objective programming problem discussed in [20].The possibility of providing reactive power support to the grid from wind farms with inverters, detailed analysis of capability curves and cost components are examined[21]. Analyzing the relationship between the active and reactive power mismatch is presented [22].

The increase in power demand for the recent years has made higher requirements from the power industry. More construction of power plants, substations and transmission lines are essential [25]. Circuit breakers are the frequently operated devices in the power grid [26]. These circuits are at times difficult to handle because of long switching period and discrete operation. This increases the cost and also lowers the efficiency of the power system networks [27, 28]. Severe blackouts have occurred recently worldwide because of lack of proper controlling [29]. This is discussed in detail in the later part of this chapter. Different approaches such as Reactive power compensation [30] and phase angle shifting [31] could be applied to increase the stability and security of the system. By Providing secure tie line connections to neighbouring utilities and regions thereby decreasing overall generation reserve requirements on both sides. Provide greater flexibility in sitting new generation. Reduce reactive power flows, thus allowing the lines to carry more active power. Reduce loop flows. Increase utilization of least cost generation. Overcome the problem of voltage fluctuations presented in [32-34].

In this paper, wind mill of 200MW capacity and FACT controllers as reactive power compensation devices are simulated for 16 bus system. The model can be compared to actual measured data from an industrial zone which it will be used in planned contingency cases to study the response of the power system for various FACT devices such as STATCOM, SVC, UPFC and SSSC.

### 1.1 Environmental impact:

In order to provide new transmission routes to supply an ever increasing worldwide demand for electrical power, it is necessary to acquire the right to convey electrical energy over a given route. It is common for environmental opposition to frustrate attempts to establish new transmission routes. FACTS technology, however allows greater throughput over existing routes, thus meeting consumer demand without the construction of new transmission lines [35].

## 2. Materials and Methods:

The reactive power procurement by compensating using ancillary devices for an industrial zone consist of 16 buses is worked out in MATLAB/Simulink environment and the results were tabulated. The sixteen bus system contains three programmable voltage source and wind mill are connected and formed a hybrid system ,the ratings of various generators are given in table 1. The distance between the buses pi lines are tabulated in the table 2, The dynamic load ratings, number of feeders and the number of transformers connected with the system is tabulated in table 3. The R, L and C parameter also given in the same table to calculate its bus admittance. The entire system consist of 39 transformers in the load end which is supplying to the load through 111 feeders. The real time data was taken from an industrial zone and it is given as input parameter for the test system and was simulated. Since reactive power is more important in industrial places, Finding out the best compensation will improve the system efficiency and stability. For four different compensation the circuit was simulated then the best values are tabulated in table 4.

## 3.Reactive Power basics in the deregulating electrical power environment:

While considering an industry almost all the loads are inductive in nature. The power factor will be poor since it acquires more lagging reactive power naturally. it is much important to compensate it. Compensation at each and every industry may lead to cause instability in the power system network which will further impinge on more practical losses including financial status of a nation. To overcome this the reactive power must be compensated in an effective manner. Using FACT controller it is possible to obtain a good solution. Initially the FACT controllers were tested for a five bus system, then applied to a sixteen bus practical test system. STATCOM giving a best solution in this case. The single line diagram is given in Figure 3.

## 4.Analysis of FACT controller :

Figure 1 shows the Reactive Power capability of inverter basics found in [23].

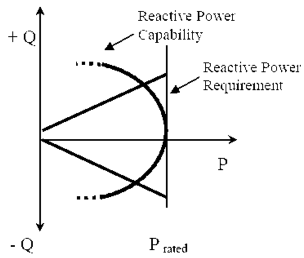
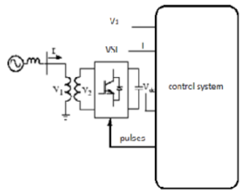
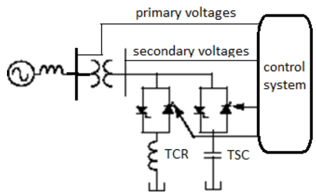



Figure 1 - Power triangle

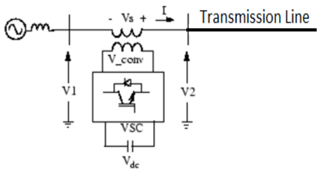
The various FACT controllers STATCOM,SVC,SSSC and UPFC are shown in figure- 2.The diagram shows FACT devices connection with the transmission line .



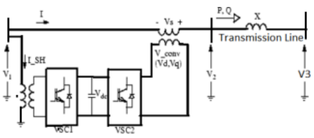

a)STATCOM controller




b)SVC controller




c)SSSC controller




d)UPFC controller

Figure 2 - FACT Controllers

### 4.1 STATCOM :

STATCOM is a regulating device which can be used to regulate the flow of reactive power in the system independent of other system parameters. STATCOM has no long term energy support on the dc side and it cannot exchange real power with the ac system. In the transmission systems, STATCOM primarily handle only fundamental reactive power exchange and provide voltage support to buses by modulating bus voltages during dynamic disturbances in order to provide better transient characteristics, improve the transient stability margins and to damp out the system oscillations due to these disturbances. STATCOM control not only reactive power but also active power in the connected lines. The STATCOM regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. When system voltage is low, the STATCOM generates reactive power (STATCOM capacitive). When system voltage is high, it absorbs reactive power (STATCOM inductive).

### 4.2 SVC :

SVC is a shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage). SVC is an important FACTS controller already widely in operation. Ratings range from 60 to 600 MVAR. SVC can be considered as a first generation.

### 4.3 SSSC :

The SSSC is one of the most recent FACTS devices for power transmission series compensation. Static Synchronous Series Compensator (SSSC) is a series compensator of FACTS family. It injects an almost sinusoidal voltage with variable amplitude. It is equivalent to an inductive or a capacitive reactance in series with the transmission line.

### 4.4 UPFC:

The UPFC is made out of two voltage-source converters (VSCs) with semiconductor devices having turn-off capability, sharing a common dc capacitor and connected to a power system through coupling transformers. The basic structure of UPFC is shown in Figure 2-d. The shunt converter is primarily used to provide the real power demand of the series converter at the common dc link terminal from the ac power system. It can also generate or absorb reactive power at its ac terminal.

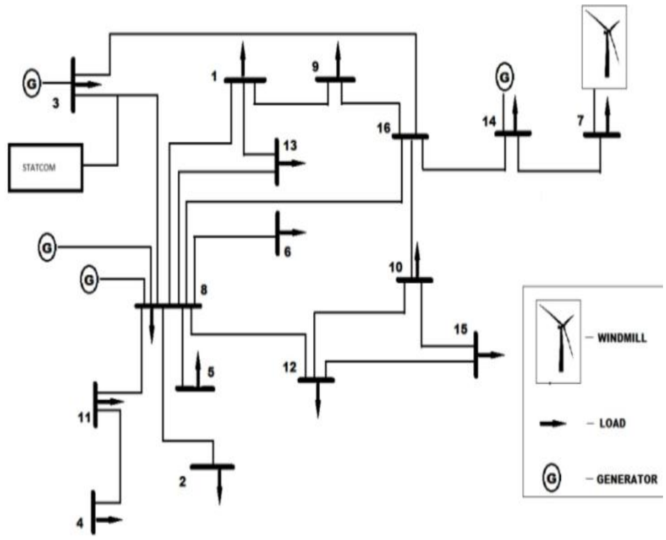



Figure 3 - Single Line diagram of the (industry zone) test system.

**Table 1: Generator ratings**

| Generator | Voltage rating | Power Rating |
|---|---|---|
| G1 | 11kV | 150 MW |
| G2 | 11kV | 100 MW |
| G3 | 11kV | 100 MW |
| Wind Power | 765 V | 200 MW |
| **Total Power** | | **550 MW** |

**Table 2: PI transmission line parameters**

| Between Buses | Line length | $L_1$-positive sequence inductance | $L_0$-positive sequence inductance | $C_1$-Positive sequence capacitance | $C_0$-Zero sequence capacitance |
|---|---|---|---|---|---|
| D2,8 | 44 | 0.041083 | 0.181562 | 5.6056E-07 | 3.41044E-07 |
| D3,8 | 44 | 0.041083 | 0.181562 | 5.6056E-07 | 3.41044E-07 |
| D1,3 | 24.7 | 0.023062 | 0.101922 | 3.1468E-07 | 1.9145E-07 |
| D3,16 | 14 | 0.013072 | 0.05777 | 1.7836E-07 | 1.08514E-07 |
| D3,8 | 22 | 0.020541 | 0.090781 | 2.8028E-07 | 1.70522E-07 |
| D1,8 | 28 | 0.026144 | 0.115539 | 3.5672E-07 | 2.17028E-07 |
| D8,13 | 13 | 0.012138 | 0.053643 | 1.6562E-07 | 1.00763E-07 |
| D8,6 | 6 | 0.005602 | 0.024758 | 7.644E-08 | 4.6506E-08 |
| D8,16 | 38.6 | 0.036041 | 0.159279 | 4.9176E-07 | 2.99189E-07 |
| D8,12 | 10.4 | 0.00971 | 0.042915 | 1.325E-07 | 8.06104E-08 |
| D12,10 | 7.6 | 0.007096 | 0.031361 | 9.6824E-08 | 5.89076E-08 |
| D8,2 | 7.5 | 0.007003 | 0.030948 | 9.555E-08 | 5.81325E-08 |
| D8,5 | 9.29 | 0.008674 | 0.038334 | 1.1835E-07 | 7.20068E-08 |
| D16,14 | 9 | 0.008403 | 0.037138 | 1.1466E-07 | 6.9759E-08 |
| D14,7 | 6.72 | 0.006274 | 0.027729 | 8.5613E-08 | 5.20867E-08 |
| D9,1 | 17.53 | 0.016368 | 0.072336 | 2.2333E-07 | 1.35875E-07 |
| D12,15 | 3 | 0.002801 | 0.012379 | 3.822E-08 | 2.3253E-08 |
| D10,16 | 15 | 0.014006 | 0.061896 | 1.911E-07 | 1.16265E-07 |
| D8,11 | 24.416 | 0.022797 | 0.10075 | 3.1106E-07 | 1.89248E-07 |
| D11,4 | 7.45 | 0.006956 | 0.030742 | 9.4913E-08 | 5.7745E-08 |
| D9,16 | 7 | 0.006536 | 0.028885 | 8.918E-08 | 5.4257E-08 |
| D1,13 | 23.3 | 0.021755 | 0.096145 | 2.9684E-07 | 1.80598E-07 |

**Table 3: Real and Reactive Power of 16 bus system (Standard test system)**

| Bus no. | P in (Mw) | Q (Mvar) | Transformer rating in MVA | No. Of feeders |
|---|---|---|---|---|
| Bus 1 | 36.23 $x10^6$ | 31.486 $x10^6$ | 3*16 | 4,3,3 |
| Bus 2 | 45.97 $x10^6$ | 64.922 $x10^6$ | 2*25,2*16 | 3,2,5,4 |
| Bus 3 | 19 $x10^6$ | 25.62 $x10^6$ | 2*16 | 4,3 |
| Bus 4 | 29.3 $x10^6$ | 30.09 $x10^6$ | 2*16,1*10 | 3,5,2 |
| Bus 5 | 35 $x10^6$ | 46.249 $x10^6$ | 3*16,1*10 | 3,3,3,2 |
| Bus 6 | 42.72 $x10^6$ | 61.644 $x10^6$ | 3*25 | 3,4,3 |
| Bus 7 | 72.02 $x10^6$ | 39.206 $x10^6$ | 2*25,2*16 | 4,2,2,4 |
| Bus 8 | 41.92 $x10^6$ | 27.253 $x10^6$ | 2*25 | 3,3 |
| Bus 9 | 15.9 $x10^6$ | 11.86 $x10^6$ | 2*10 | 3,3 |
| Bus 10 | 36.45 $x10^6$ | 30.68 $x10^6$ | 3*16 | 3,2,2 |
| Bus 11 | 15.6 $x10^6$ | 12.516 $x10^6$ | 2*10 | 3,3 |
| Bus 12 | 26.78 $x10^6$ | 42.224 $x10^6$ | 2*25 | 2,2 |
| Bus 13 | 15.6 $x10^6$ | 11.98 $x10^6$ | 2*10 | 2,2 |
| Bus 14 | 11.82 $x10^6$ | 10.795 $x10^6$ | 1*16 | 2 |
| Bus 15 | 9.72 $x10^6$ | 12.709 $x10^6$ | 2*8 | 1,1 |
| Bus 16 | No load | - | - | - |
| **Total no of transformers 39** | | | | **Total no of feeders - 111** |

### 4.1 Economic aspects:

The fast reactive sources are generators, synchronous condensers and power electronics-based FACT controllers. The cost for using FACT controllers are assumed proportional to the capital investment on the FACT devices, the amount of the reactive power output purchased from the provider, and for the value they provide by improving the power factor.

The cost of FACT devices are very high. The ISO will procure the required reactive service, taking technical feasibility and economic efficiency in to account [1].The incurred costs will then be fully allocated to different consumers in an equitable and a transparent manner.

$C_j(Q_j^{facts})$ α Fixed Cost + Variable Cost.
Fixed cost = $CC_j\ (Q_j^{facts})$
Variable cost = $(DP_j^{FACTS} * Q_j^{FACTS})$ + Power Factor improvement.
$C_j(Q_j^{facts})$ = Cost of Purchasing reactive power from the provider at $j^{th}$ location.

$DP_j^{FACTS}$ = depreciation cost of the FACT controller.
$Q_j^{FACTS}$ = Reactive injection at $j^{th}$ location.

The Reactive Power market clearing should consider certain parameters and topology of the system and its operating constraints are notified in [24] which considering the distribution generators. The cost of reactive power compensated by STATCOM is noticed in [36].

## TABLE 4 : Test results of STATCOM at various buses:

| Bus no. | **Before compensation** | | **STATCOM at bus 1** | | **STATCOM at bus 2** | | **STATCOM at bus 3** | | **STATCOM at bus 4** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **P** | **Q** | **P** | **Q** | **P** | **Q** | **P** | **Q** | **P** | **Q** |
| 1 | 2.638x10$^{7}$ | 5.64 x10$^{6}$ | 100 x10$^{6}$ | -4.5 x10$^{5}$ | 1.13 x10$^{8}$ | -3400 | **140 x10$^{6}$** | **-150** | 1.3 x10$^{8}$ | 0.5 x10$^{4}$ |
| 2 | 4.695x10$^{5}$ | 7.37x10$^{4}$ | 5.2 x10$^{5}$ | -50 | 0.65 x10$^{6}$ | -2.22 x10$^{4}$ | **6 x10$^{5}$** | **-40** | 2.3 x10$^{6}$ | -500 |
| 3 | 1.178x10$^{7}$ | 2.24 x10$^{6}$ | 99.2 x10$^{6}$ | -1.2 x10$^{5}$ | 2.2 x10$^{8}$ | -1.3 x10$^{6}$ | **120 x10$^{6}$** | **-1.5 x10$^{5}$** | 2.2 x10$^{8}$ | -2 x10$^{6}$ |
| 4 | 2.759 x10$^{6}$ | 6.14 x10$^{5}$ | 2.8 x10$^{6}$ | 300 | 1.2 x10$^{7}$ | -2800 | **3.8 x10$^{6}$** | **-300** | 1.8 x10$^{6}$ | -0.8 x10$^{5}$ |
| 5 | 2.85x10$^{7}$ | 2.7 x10$^{4}$ | 5 x10$^{5}$ | 35 | 1.88 x10$^{6}$ | -200 | **0.5 x10$^{6}$** | **-30** | 0.3 x10$^{7}$ | -361 |
| 6 | 4.6 x10$^{6}$ | 8.95 x10$^{5}$ | 50 x10$^{6}$ | -800 | 2.1 x10$^{7}$ | -0.5 x10$^{4}$ | **6 x10$^{6}$** | **-600** | 0.3 x10$^{8}$ | -0.5 x10$^{4}$ |
| 7 | 443 | 87.5 | 100 x10$^{6}$ | -6 x10$^{6}$ | 6.44 x10$^{6}$ | -1.6 x10$^{5}$ | **9.5 x10$^{6}$** | **-7.5 x10$^{5}$** | 1 x10$^{7}$ | -2.6 x10$^{5}$ |
| 8 | 5.33 x10$^{6}$ | 1.02 x10$^{6}$ | 58.5 x10$^{6}$ | -1.7 x10$^{4}$ | 1.1 x10$^{8}$ | -1.8 x10$^{5}$ | **60 x10$^{6}$** | **-2 x10$^{4}$** | 1.2 x10$^{8}$ | -1 x10$^{6}$ |
| 9 | 7.55 x10$^{5}$ | 1.44 x10$^{5}$ | 1.5 x10$^{6}$ | -2000 | 4 x10$^{6}$ | -0.5 x10$^{4}$ | **1.5 x10$^{6}$** | **-2000** | 4.21 x10$^{6}$ | -0.42 x10$^{4}$ |
| 10 | 3.06x10$^{6}$ | 6.35 x10$^{5}$ | 1.5x10$^{6}$ | 2000 | 5.4 x10$^{6}$ | 1.8 x10$^{4}$ | **1.5 x10$^{6}$** | **2000** | 5.9 x10$^{6}$ | 3 x10$^{4}$ |
| 11 | 3.61 x10$^{6}$ | 8.18x10$^{5}$ | 5 x10$^{6}$ | 200 | 1.8 x10$^{7}$ | -1200 | **5 x10$^{6}$** | **-200** | 1.6 x10$^{7}$ | -1000 |
| 12 | 12.13 x10$^{4}$ | 3.01 x10$^{4}$ | 2 x10$^{5}$ | 1200 | 7.2 x10$^{5}$ | -400 | **2 x10$^{5}$** | **500** | 8 x10$^{5}$ | 500 |
| 13 | 1.077x10$^{7}$ | 2.81 x10$^{6}$ | 13 x10$^{6}$ | -200 | 4.4 x10$^{7}$ | -1100 | **14 x10$^{6}$** | **-140** | 4.8 x10$^{7}$ | -1800 |
| 14 | 117.5 | 29 | 45 x10$^{6}$ | -3 x10$^{6}$ | 8 x10$^{6}$ | -3.2 x10$^{5}$ | **4 x10$^{6}$** | **-3 x10$^{5}$** | 3.26 x10$^{6}$ | -2.4 x10$^{5}$ |
| 15 | 14.3 x10$^{4}$ | 3.23 x10$^{4}$ | 6 x10$^{5}$ | 3000 | 2.2 x10$^{6}$ | 1.7 x10$^{4}$ | **0.5 x10$^{6}$** | **2000** | 2.6 x10$^{6}$ | 0.4 x10$^{5}$ |
| 16 | - | - | 35 x10$^{6}$ | 2 x10$^{5}$ | 1.24 x10$^{8}$ | -5.65 x10$^{5}$ | **35.5 x10$^{6}$** | **-0.8 x10$^{5}$** | 1.34 x10$^{6}$ | -1 x10$^{6}$ |
| **Total power** | 70.0633 x10$^{6}$ | 14.9792x10$^{6}$ | 518.7 x10$^{6}$ | -9.3 x10$^{6}$ | 691.3 x10$^{6}$ | -2.56 x10$^{6}$ | **402.6 x10$^{6}$** | **-1.2 x10$^{6}$** | 731.9 x10$^{6}$ | -4.5 x10$^{6}$ |

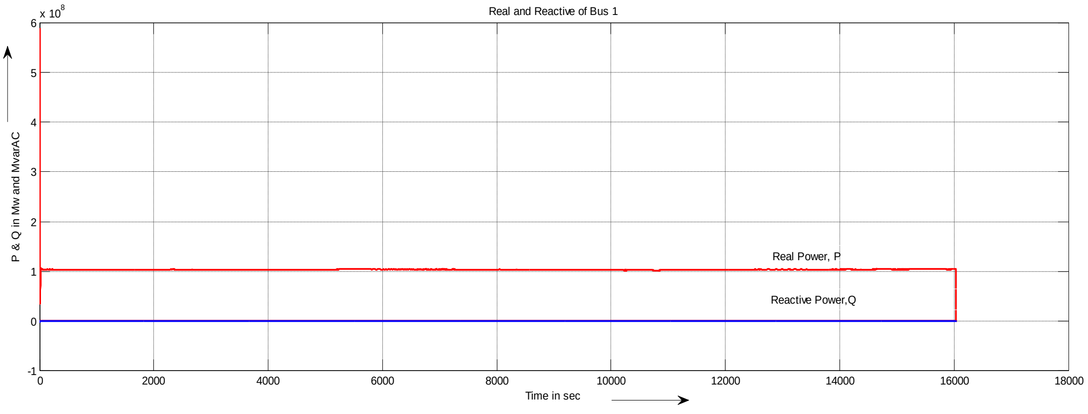
| Bus no. | **STATCOM at bus 5** | | **STATCOM at bus 6** | | **STATCOM at bus 7** | | **STATCOM at bus 8** | | **STATCOM at bus 9** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **P** | **Q** | **P** | **Q** | **P** | **Q** | **P** | **Q** | **P** | **Q** |
| 1 | 1.13 x10$^{8}$ | -4000 | 1.2 x10$^{8}$ | -6300 | 9.2 x10$^{7}$ | -1.785 x10$^{4}$ | 79.45 x10$^{6}$ | -2000 | 1.09 x10$^{8}$ | -240 |
| 2 | 2 x10$^{6}$ | -250 | 2.3 x10$^{6}$ | -500 | 1.5 x10$^{6}$ | -1200 | 1.4 x10$^{6}$ | -150 | 2 x10$^{6}$ | -25 |
| 3 | 2.17 x10$^{8}$ | -1.34 x10$^{6}$ | 2.24 x10$^{8}$ | -2.4 x10$^{6}$ | 1.14 x10$^{8}$ | -3.42 x10$^{6}$ | 1.7 x10$^{6}$ | -7 x10$^{5}$ | 2.02 x10$^{8}$ | -10 x10$^{4}$ |
| 4 | 1.2 x10$^{7}$ | -2700 | 1.3 x10$^{7}$ | -0.5*10^4 | 9.55 x10$^{6}$ | -1.06 x10$^{4}$ | 7.8 x10$^{6}$ | -1400 | 1.11 x10$^{7}$ | -200 |
| 5 | 8.15 x10$^{5}$ | 750 | 2 x10$^{6}$ | -400 | 1.4 x10$^{6}$ | -1100 | 1.245 x10$^{6}$ | -123 | 1.752 x10$^{6}$ | -12 |
| 6 | 2 x10$^{7}$ | -0.5 x10$^{4}$ | 3.5 x10$^{6}$ | -0.25*10^6 | 1.42 x10$^{7}$ | -2.41 x10$^{4}$ | 13.5 x10$^{6}$ | -2675 | 1.89 x10$^{7}$ | -300 |
| 7 | 9 x10$^{6}$ | -1.5 x10$^{4}$ | 2 x10$^{7}$ | -2*10^6 | 6 x10$^{7}$ | -8 x10$^{6}$ | 3.2 x10$^{6}$ | -6 x10$^{4}$ | 4 x10$^{7}$ | -2 x10$^{6}$ |
| 8 | 1.11 x10$^{8}$ | -2.68 x10$^{5}$ | 1.1 x10$^{8}$ | -0.25*10^6 | 6.15 x10$^{7}$ | -2.25 x10$^{5}$ | 90 x10$^{6}$ | -9 x10$^{4}$ | 1 x10$^{8}$ | -1.6 x10$^{4}$ |
| 9 | 3.9 x10$^{6}$ | -4211.9 | 4.2 x10$^{6}$ | -0.42*10^4 | 2.3 x10$^{6}$ | -2400 | 2.85 x10$^{6}$ | -3200 | 8.2 x10$^{6}$ | 6750 |
| 10 | 5.4 x10$^{6}$ | 1.8 x10$^{4}$ | 0.6 x10$^{7}$ | 0.4*10^5 | 4.2 x10$^{6}$ | 8.55 x10$^{4}$ | 3.5 x10$^{6}$ | 9500 | 0.49 x10$^{7}$ | 750 |
| 11 | 1.81 x10$^{7}$ | -1375 | 2 x10$^{7}$ | -2000 | 1.37 x10$^{7}$ | 6245 | 12 x10$^{6}$ | -730 | 1.72 x10$^{7}$ | -100 |
| 12 | 7 x10$^{5}$ | -500 | - | - | 6.5 x10$^{5}$ | -3600 | 0.47 x10$^{6}$ | 700 | 6.52 x10$^{5}$ | 20 |
| 13 | 4.35 x10$^{7}$ | -1000 | 4.7 x10$^{7}$ | -2000 | 3.5 x10$^{7}$ | -5550 | 30 x10$^{6}$ | -500 | 4.2 x10$^{7}$ | -80 |
| 14 | 1.4 x10$^{7}$ | 1.4 x10$^{6}$ | 0.75 x10$^{7}$ | 0.25*10^6 | 0.5 x10$^{7}$ | -0.8 x10$^{6}$ | 0.13 x10$^{6}$ | -2 x10$^{5}$ | 1 x10$^{7}$ | -1 x10$^{6}$ |
| 15 | 2.2 x10$^{6}$ | 1.75 x10$^{4}$ | 2.5 x10$^{6}$ | 4*10^4 | 3 x10$^{6}$ | 0.5 x10$^{5}$ | 1.4 x10$^{6}$ | 1.05 x10$^{4}$ | 1 x10$^{7}$ | -1 x10$^{6}$ |
| 16 | 1.22 x10$^{8}$ | -5 x10$^{5}$ | 1.35 x10$^{8}$ | -1.2*10^6 | 1 x10$^{6}$ | 3.5 x10$^{6}$ | 80 x10$^{6}$ | -2.867 x10$^{5}$ | 10.5 x10$^{7}$ | -2 x10$^{4}$ |
| **Total power** | 694 x10$^{6}$ | -7 x10$^{6}$ | 710 x10$^{6}$ | -5.7 x10$^{6}$ | 518 x10$^{6}$ | -8.9 x10$^{6}$ | 328 x10$^{6}$ | -13.2 x10$^{5}$ | 682.7 x10$^{6}$ | -4.1 x10$^{6}$ |

| Bus no. | STATCOM at bus 10 | | STATCOM at bus 11 | | STATCOM at bus 12 | | STATCOM at buse 13 | | STATCOM at bus 14 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **P** | **Q** | **P** | **Q** | **P** | **Q** | **P** | **Q** | **P** | **Q** |
| 1 | 1 x10$^{8}$ | -0.4 x10$^{4}$ | 8 x10$^{7}$ | -0.5 x10$^{4}$ | 1.14 x10$^{8}$ | -3800 | 29 x10$^{6}$ | -300 | 1.2 x10$^{8}$ | -3800 |
| 2 | 2 x10$^{6}$ | -280 | 1.4 x10$^{6}$ | -380 | 2.1 x10$^{6}$ | -250 | 0.5 x10$^{6}$ | -20 | 2.1 x10$^{6}$ | -250 |
| 3 | 2 x10$^{8}$ | -1.4 x10$^{6}$ | 1.5 x10$^{8}$ | -1.5 x10$^{6}$ | 2.2 x10$^{8}$ | -1.45 x10$^{6}$ | 100 x10$^{6}$ | -9.75 x10$^{4}$ | 2.2 x10$^{8}$ | -1.3 x10$^{6}$ |
| 4 | 1 x10$^{7}$ | -3000 | 3.2 x10$^{6}$ | -620 | 1.2 x10$^{7}$ | -0.25 x10$^{4}$ | 2.75 x10$^{6}$ | -200 | 12 x10$^{6}$ | -0.25 x10$^{4}$ |
| 5 | 1.75 x10$^{6}$ | -220 | 1.15 x10$^{6}$ | -267 | 1.8 x10$^{6}$ | -200 | 4.45 x10$^{6}$ | -20 | 1.9 x10$^{6}$ | -210 |
| 6 | 2 x10$^{7}$ | -0.5 x10$^{4}$ | 1.48 x10$^{7}$ | -6500 | 2.06 x10$^{7}$ | -0.5 x10$^{4}$ | 50 x10$^{6}$ | -400 | 2.1 x10$^{7}$ | -0.5 x10$^{4}$ |
| 7 | 2 x10$^{7}$ | -5 x10$^{6}$ | 0.5 x10$^{7}$ | -0.45 x10$^{6}$ | 0.5 x10$^{8}$ | -4 x10$^{6}$ | 10 x10$^{6}$ | -1 x10$^{6}$ | 2 x10$^{7}$ | -2 x10$^{6}$ |
| 8 | 1 x10$^{8}$ | -0.2 x10$^{6}$ | 0.8 x10$^{8}$ | -2.1 x10$^{6}$ | 1.1 x10$^{8}$ | -2 x10$^{5}$ | 56 x10$^{6}$ | -1.4 x10$^{4}$ | 1.08 x10$^{8}$ | -1.8 x10$^{5}$ |
| 9 | 3.4 x10$^{6}$ | -4000 | 3 x10$^{6}$ | -4000 | 0.4 x10$^{7}$ | -0.4 x10$^{4}$ | 1.15 x10$^{6}$ | -1500 | 4.2 x10$^{6}$ | -4400 |
| 10 | 2 x10$^{7}$ | -1.5 x10$^{5}$ | 3.58 x10$^{6}$ | 3.2 x10$^{4}$ | 5.8 x10$^{6}$ | -1.2 x10$^{4}$ | 1.3 x10$^{6}$ | 1200 | 5.3 x10$^{6}$ | 1.7 x10$^{4}$ |
| 11 | 1.8 x10$^{7}$ | -1500 | 4.8 x10$^{7}$ | -0.6 x10$^{6}$ | 1.8 x10$^{7}$ | -1200 | 4.4 x10$^{6}$ | -100 | 0.51 x10$^{7}$ | 1.8 x10$^{4}$ |
| 12 | 6 x10$^{5}$ | -1 x10$^{4}$ | 5 x10$^{5}$ | 3000 | 1.8 x10$^{5}$ | 150 | 1.7 x10$^{5}$ | 600 | 7.2 x10$^{5}$ | -500 |
| 13 | 4 x10$^{7}$ | 1200 | 3.1 x10$^{7}$ | -1500 | 4.4 x10$^{7}$ | -1200 | 90 x10$^{6}$ | -2 x10$^{5}$ | 4 x10$^{7}$ | -1200 |
| 14 | 1 x10$^{7}$ | -1 x10$^{6}$ | 4 x10$^{6}$ | -2.92 x10$^{5}$ | 1 x10$^{7}$ | -2 x10$^{6}$ | 4 x10$^{6}$ | -2000 | 0.4 x10$^{8}$ | -3 x10$^{6}$ |
| 15 | 9 x10$^{5}$ | 4000 | 1.7 x10$^{6}$ | 2.7 x10$^{4}$ | 1.75 x10$^{6}$ | 1 x10$^{4}$ | 0.5 x10$^{6}$ | 1800 | 2.2 x10$^{6}$ | 1.6 x10$^{4}$ |
| 16 | 1.3 x10$^{8}$ | -1 x10$^{6}$ | 8 x10$^{7}$ | -1 x10$^{6}$ | 1.2 x10$^{8}$ | -0.5 x10$^{6}$ | 28 x10$^{6}$ | -0.5 | 1.21 x10$^{8}$ | -5 x10$^{5}$ |
| **Total power** | 676.65 x10$^{6}$ | -10.13 x10$^{6}$ | 507.33 x10$^{6}$ | -5.89 x10$^{6}$ | 627.57 x10$^{6}$ | -8.17 x10$^{6}$ | 382 x10$^{6}$ | -1.31 x10$^{6}$ | 723.52 x10$^{6}$ | -6.94 x10$^{6}$ |

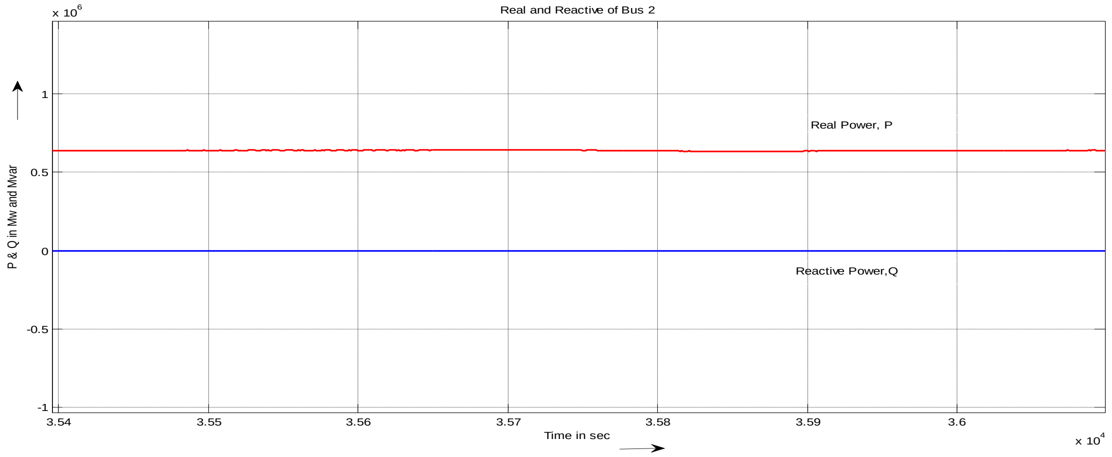
| Bus no. | STATCOM at bus 15 | | STATCOM at 4 buses 16 | | STATCOM at 4 buses (1,3,8,13) | | STATCOM at buses 1,8 | | STATCOM at buses (3,13) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **P** | **Q** | **P** | **Q** | **P** | **Q** | **P** | **Q** | **P** | **Q** |
| 1 | 1.15 x10$^{8}$ | -4000 | 2.6 x10$^{7}$ | -300 | **26 x10$^{6}$** | **-1000** | 1x10$^{8}$ | -1 x10$^{6}$ | 1.17 x10$^{7}$ | -50 |
| 2 | 2.1 x10$^{6}$ | -250 | 4.5 x10$^{5}$ | -20 | **0.1 x10$^{6}$** | **0** | 0.4 x10$^{6}$ | -50 | 2 x10$^{5}$ | -4 |
| 3 | 2.2 x10$^{8}$ | -1.35 x10$^{6}$ | 7.78 x10$^{7}$ | -2.3 x10$^{4}$ | **51 x10$^{6}$** | **-3000** | 1 x10$^{8}$ | -0.4 x10$^{6}$ | 0.6 x10$^{8}$ | -1.6 x10$^{4}$ |
| 4 | 1.2 x10$^{7}$ | -0.25 x10$^{4}$ | 2.5 x10$^{6}$ | -200 | **0.75 x10$^{6}$** | **0** | 2.5 x10$^{6}$ | -500 | 1.5 x10$^{6}$ | 50 |
| 5 | 1.85 x10$^{6}$ | -220 | 4 x10$^{5}$ | -20 | **0.12 x10$^{5}$** | **0** | 4 x10$^{5}$ | -50 | 2 x10$^{5}$ | -4 |
| 6 | 2.1 x10$^{7}$ | -0.5 x10$^{4}$ | 4.4 x10$^{6}$ | -400 | **1.3 x10$^{6}$** | **-25** | 4 x10$^{6}$ | -1000 | 3 x10$^{6}$ | -100 |
| 7 | 0.5 x10$^{8}$ | -3.8 x10$^{6}$ | 2 x10$^{7}$ | -4 x10$^{6}$ | **100 x10$^{6}$** | **-2 x10$^{6}$** | 1 x10$^{7}$ | 1 x10$^{6}$ | 2.8 x10$^{7}$ | -2 x10$^{6}$ |
| 8 | 1.08 x10$^{8}$ | -1.8 x10$^{5}$ | 4.4 x10$^{7}$ | -2000 | **30 x10$^{6}$** | **0** | 0.5 x10$^{8}$ | -1 x10$^{4}$ | 4 x10$^{7}$ | -3000 |
| 9 | 4 x10$^{6}$ | -4500 | 7.74 x10$^{5}$ | -680 | **0.3 x10$^{6}$** | **-500** | 1.2x10$^{6}$ | -2000 | 6.8 x10$^{5}$ | -1000 |
| 10 | 6 x10$^{6}$ | -0.5 x10$^{5}$ | 6.4 x10$^{5}$ | 600 | **0.38** | **100** | 1 x10$^{6}$ | 0.5 x10$^{4}$ | 6 x10$^{5}$ | 200 |
| 11 | 1.8 x10$^{7}$ | -1200 | 3.98 x10$^{6}$ | -100 | **1.2 x10$^{6}$** | **0** | 4 x10$^{6}$ | -200 | 2 x10$^{6}$ | -25 |
| 12 | 0.7 x10$^{6}$ | -8000 | 1.3 x10$^{5}$ | -400 | **0.48 x10$^{5}$** | **200** | 1.5 x10$^{5}$ | 2000 | 1 x10$^{5}$ | 250 |
| 13 | 4.4 x10$^{7}$ | -1200 | 9.7 x10$^{6}$ | -92 | **22 x10$^{6}$** | **-1000** | 0.5 x10$^{6}$ | 1 x10$^{5}$ | 3 x10$^{5}$ | 1 x10$^{5}$ |
| 14 | 0.25 x10$^{8}$ | -1.8 x10$^{6}$ | 1.25 x10$^{7}$ | -2 x10$^{6}$ | **200 x10$^{6}$** | **-1 x10$^{6}$** | 0.5 x10$^{7}$ | 0.5 x10$^{6}$ | 0.5 x10$^{7}$ | -1 x10$^{6}$ |
| 15 | 1 x10$^{6}$ | 1 x10$^{4}$ | 2.25 x10$^{5}$ | 300 | **0.15 x10$^{6}$** | **200** | 4 x10$^{5}$ | 1 x10$^{4}$ | 2.5 x10$^{5}$ | 400 |
| 16 | 1.2 x10$^{8}$ | -0.5 x10$^{6}$ | 6 x10$^{7}$ | -3.5 x10$^{4}$ | **8 x10$^{6}$** | **500** | 0.25 x10$^{8}$ | -1.4 x10$^{5}$ | 2 x10$^{7}$ | -2 x10$^{4}$ |
| **Total power** | 746.98 x10$^{6}$ | -7.696 x10$^{6}$ | 263.49 x10$^{6}$ | -6.06 x10$^{6}$ | **439.6** | **1 x10$^{6}$** | 308.5 x10$^{6}$ | 0.0632 x10$^{6}$ | 317.83 x10$^{6}$ | -2.93 x10$^{6}$ |

Figure 3 - Scope readings of reactive power compensation done using using statcom placed at bus 3

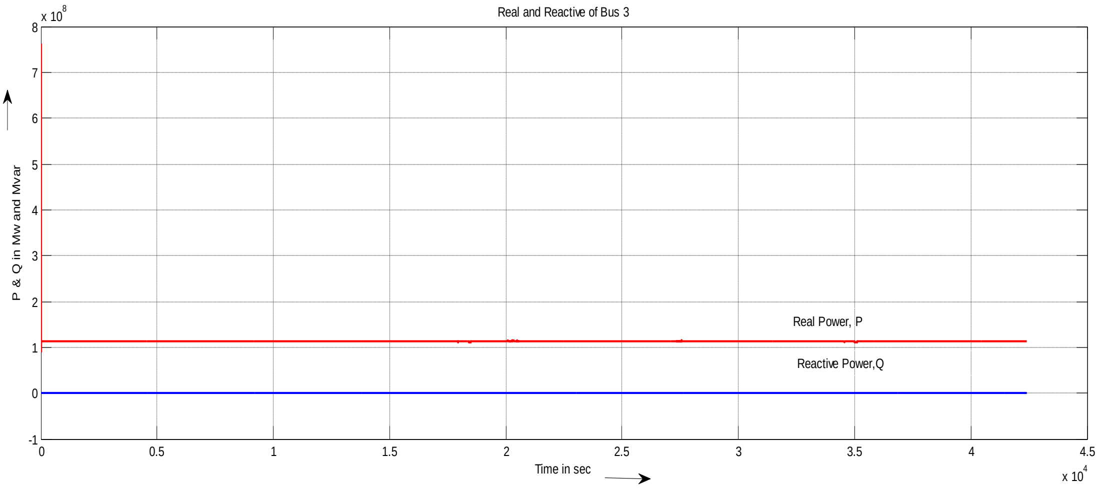
AT BUS 1



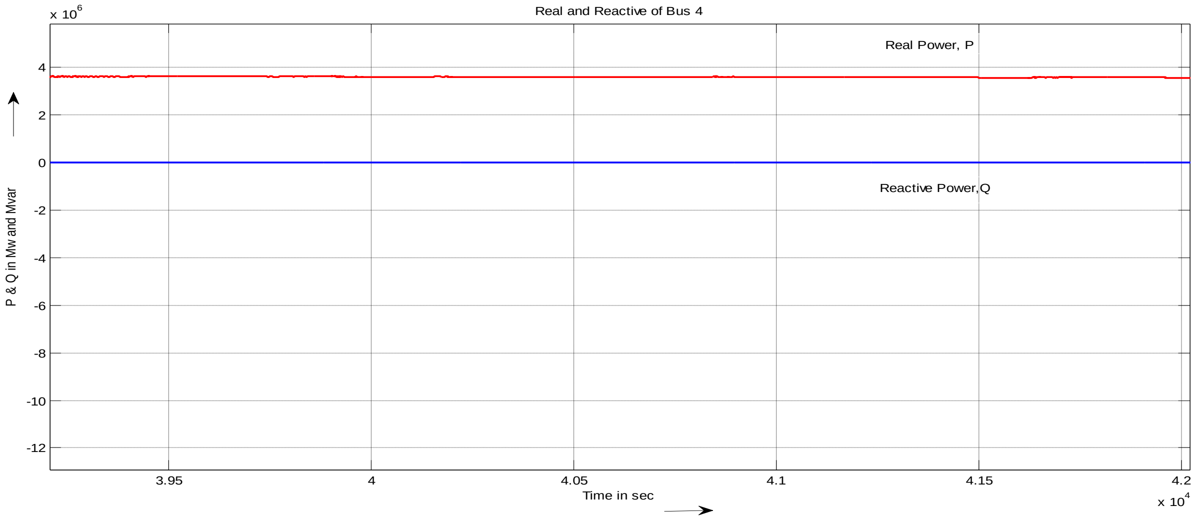

AT BUS 2



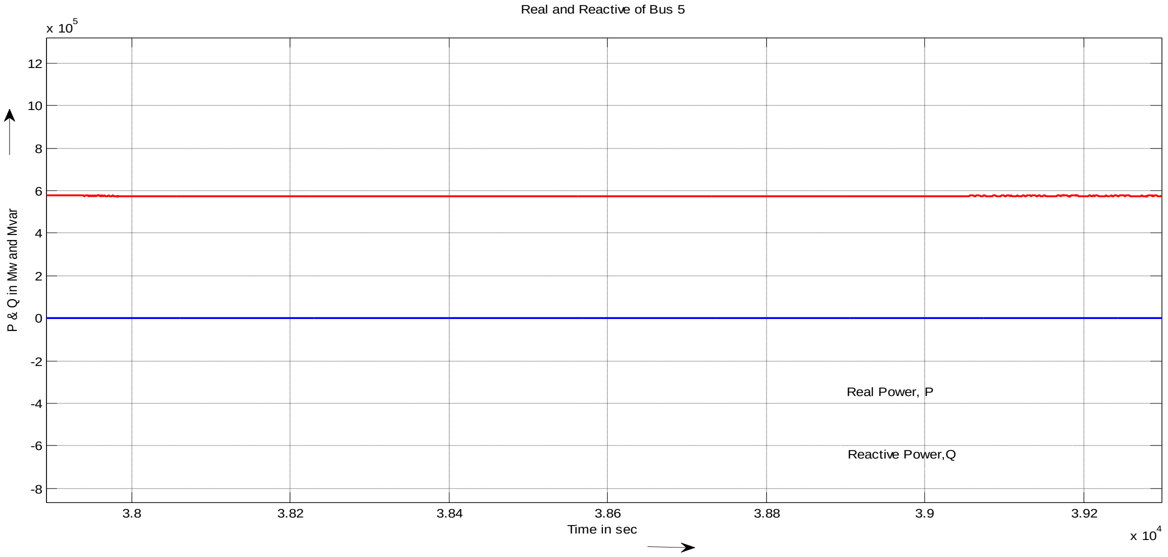

AT BUS 3



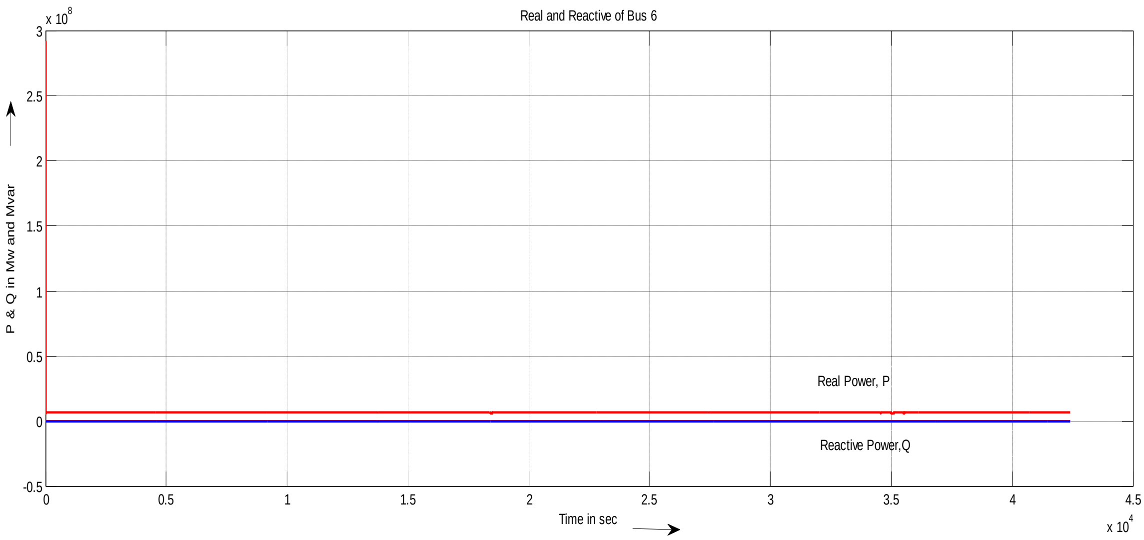
ATBUS 4



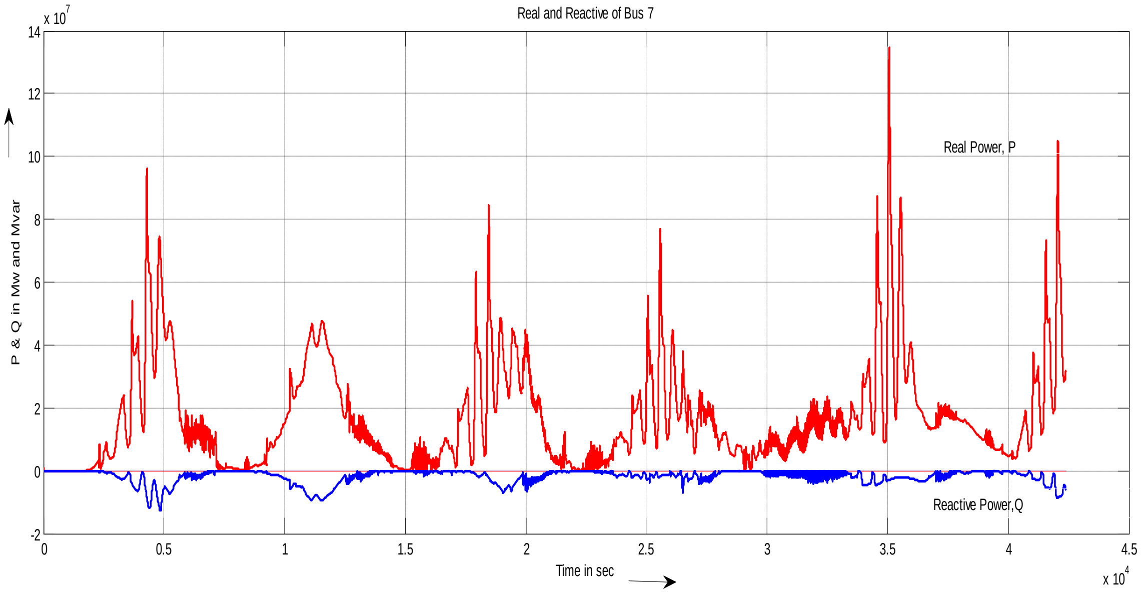

AT BUS 5



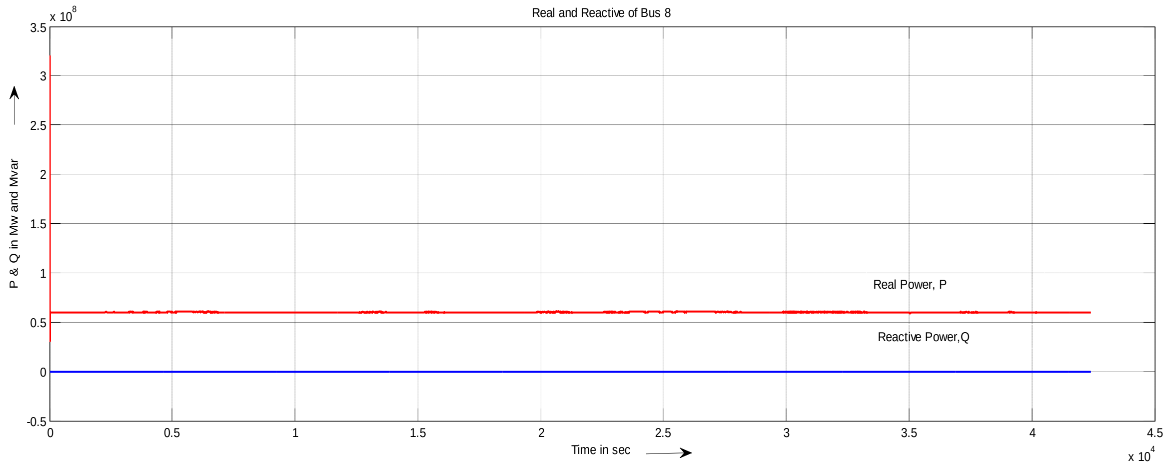

AT BUS 6



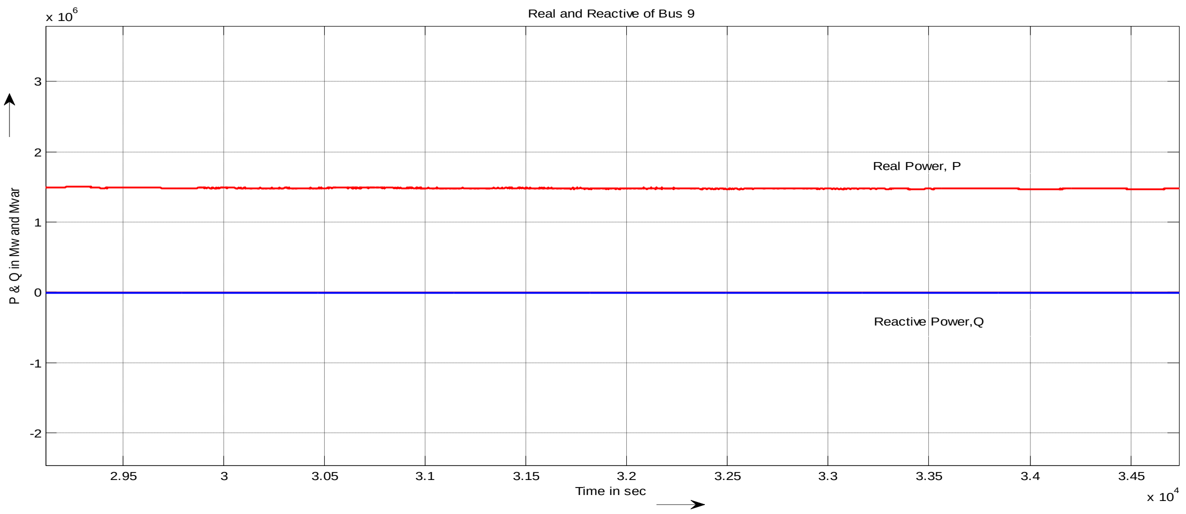
AT BUS 7



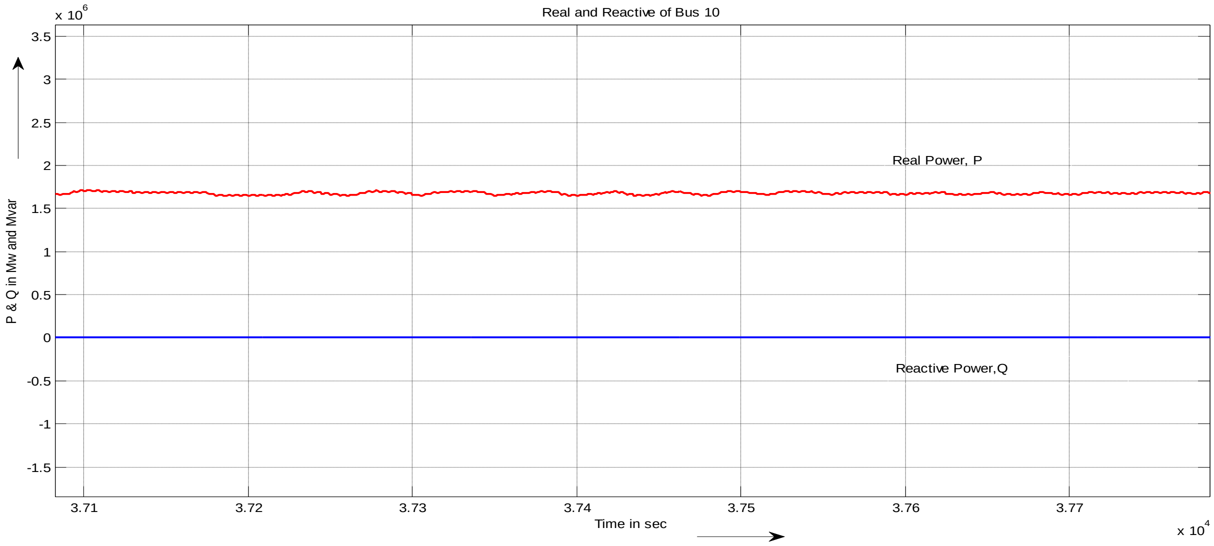

AT BUS 8



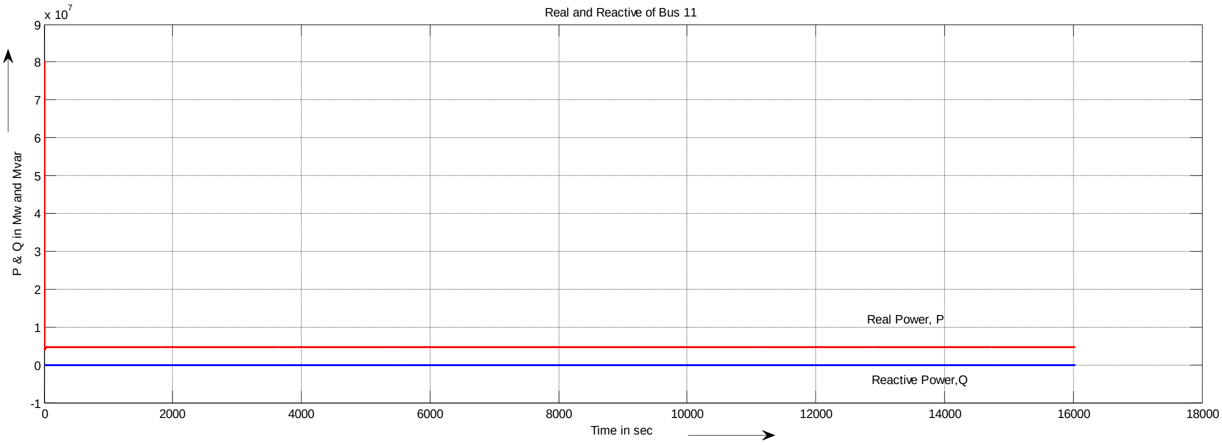

AT BUS 9



AT BUS 10

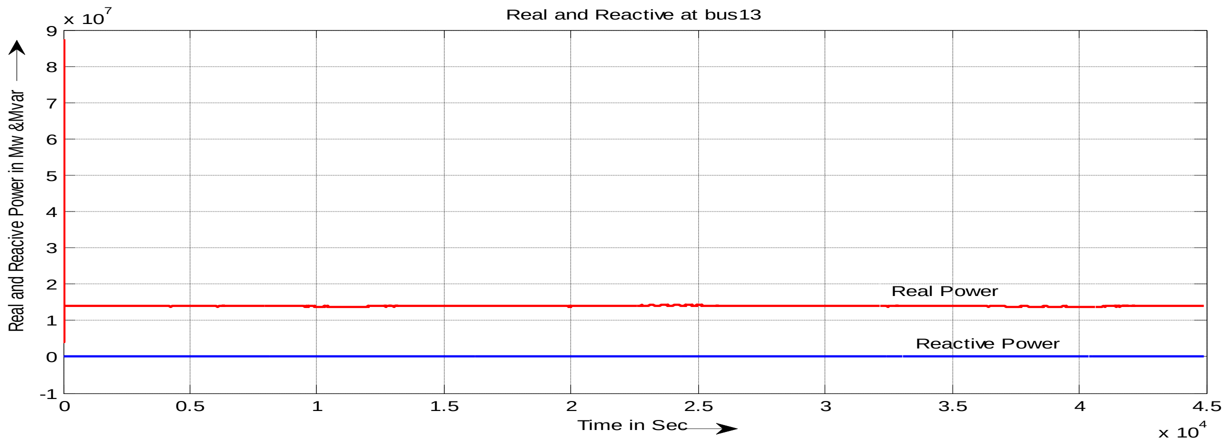



AT BUS 11

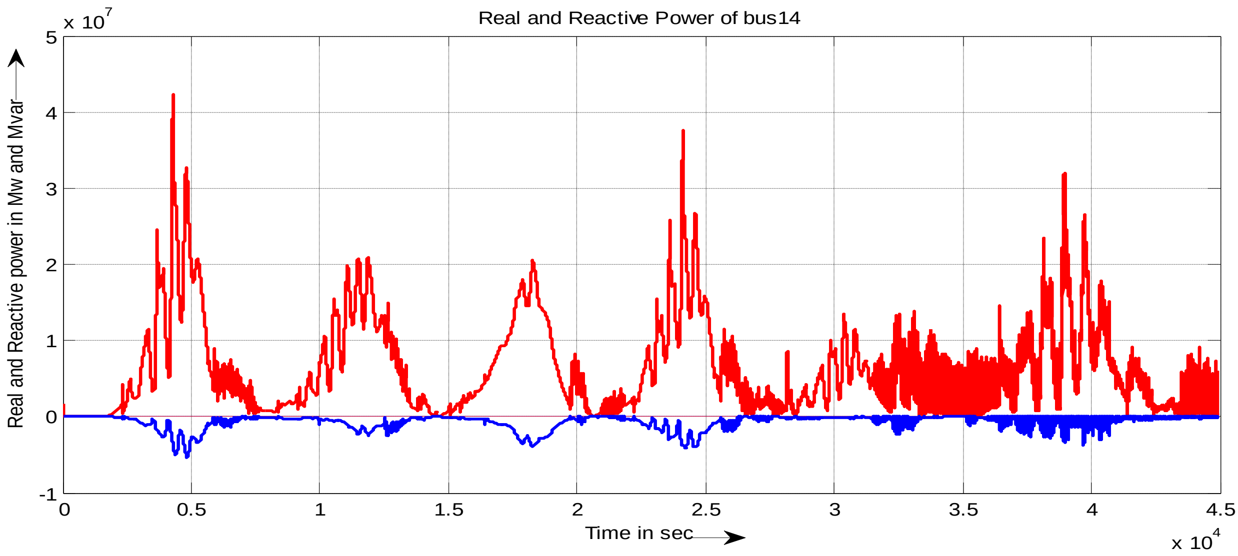



AT BUS 12

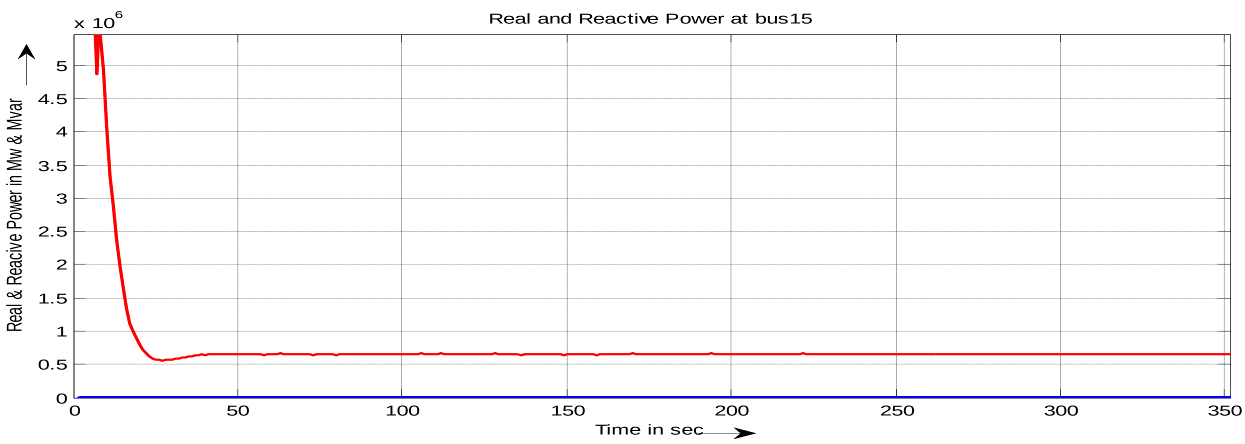
AT BUS 13



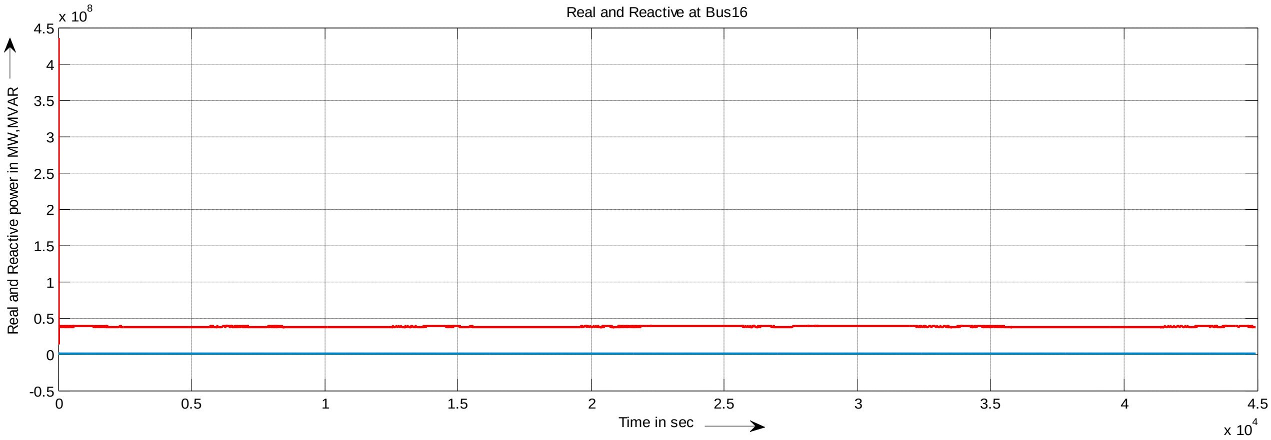

AT BUS 14




AT BUS 15



AT BUS 16




### 4.2 Result Analysis :

When the STATCOM is placed at bus 3, the reactive power is over compensated about 1 Mvar. When four STATCOMs are placed at buses 1, 3, 8 and 13, the reactive power is compensated but lagging by 1.3 Mvar. (Shaded portion illustrated in Table 4) By considering the cost, later one will be high cost and the former will be the best one but the load will be fluctuating in nature. So, cost effective and leading reactive power by one Mvar can be concluded as best result.

## 5. Conclusion:

In this paper, an extensive simulation of sixteen bus industrial zone power distribution system has been done focussing on reactive power reduction and enhancing the real power of distribution line. Among four FACT controller SVC, SSSC, UPFC and STATCOM, STATCOM giving good results, which improve the transmission efficiency effectively. When the STATCOM connected to bus 3, the compensation is effective as per the test results.

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