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# Analysis of T-STATCOM-6, 12, 48 Pulse

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## ABSTRACT

*This paper presents the performance and comparative analysis of Static Synchronous Compensator (STATCOM), based on 6, 12 and 48-pulse VSC configuration. STATCOM is implemented for regulation of the voltage at the Point of Common Coupling (PCC) bus which has time variable loads. The dq decoupled current control strategy is used for implementation of STATCOM, where modulation index M and phase angle Φ are varied for achieving voltage regulation at the PCC bus. The 6, 12 and 48-pulse configurations are compared and analyzed on the basis of Total Harmonic Distortion (THD) and time response parameters such as rise time, maximum overshoot, settling time. The simulation of various configurations of STATCOM is carried out using power system blockset in MATLAB/ Simulink platform.*

***KEYWORDS:*** *FACTS, STATCOM, decoupled current control system, Voltage Sourced Converter, Total Harmonic Distortion.*



## I. INTRODUCTION

Reactive power is an important aspect of electrical power systems. Reactive power in the system needs to be effectively controlled as it may lead to many problems such as voltage instability, voltage fluctuations, power quality problems, poor system power factor and reduce the power transfer compatibility. Thus, reactive power compensation is necessary to improve the performance and stability of the power systems by maintaining a flat voltage profile [1].

Traditionally, reactive power compensation was done using capacitor banks, synchronous condensers and mechanically switched capacitors or inductors. The invention of Flexible AC transmission System (FACTS) devices has overcome the limitations of the traditional methods of reactive power compensation [2]. FACTS devices have the capability to accommodate changes in operating conditions of transmission systems while maintaining sufficient steady state and transient margins [3]. The Static Synchronous Compensator (STATCOM) is a shunt connected FACTS device, which is capable of providing both capacitive and inductive compensation [4]. It can maintain maximum output current which is not dependent on the AC system voltage. STATCOM is mainly used for controlling voltage of the transmission line, increasing power flow, improving the power system stability and damping power oscillations [5]. There are various topologies of implementing a STATCOM. A detailed explanation of STATCOM configurations, controller and its uses are given in [6]. It has been observed that the use of multi- pulse configuration for STATCOM has helped in achieving a pure sine waveform [7], [8]. These configurations have eliminated the need of filters for harmonic reduction.

The Type I inverter allows the instantaneous values of both $\varphi$ (phase angle between PCC bus voltage and STATCOM voltage) and M (modulation index) to be varied for control purposes. In Type II inverters M (modulation index) is a constant factor, and the only available control input is the phase angle, $\varphi$ [9]. The phase angle between the ac voltages produced by two sets of three-level 24-pulse VSCs is varied for controlling the magnitude of the converter ac voltage which in turn controls the reactive power of the STATCOM [10]. The decoupled current control scheme is used to control the real power (to maintain the dc-link voltage) and reactive power independently [11].

This paper presents the implementation of two level 48-pulse ± 100 MVA STATCOM using decoupled current control strategy for regulation of voltage at the PCC bus. Section II explain the operating principle of STATCOM. Section III describes control strategy of STATCOM. Section IV explains different STATCOM configurations. Section V gives the results of the MATLAB simulation of 48-pulse STATCOM. Section VI presents the comparison of results of 6, 12 and 48-pulse STATCOM. Conclusions are explained in Section VII.

## II. OPERATING PRINCIPLE OF STATCOM

The operation of STATCOM for voltage regulation is depicted schematically in Fig. 1.

DC voltage is provided by the charged capacitor $C_{dc}$ and using this voltage, the converter produces controllable three- phase output voltages which has frequency same as that of the frequency of AC power system. The converter output voltage is in phase with AC system voltage. The converter and the AC system are coupled through a very small (0.1-0.15p.u.) reactance which consists of shunt inductance of the coupling transformer. By changing the magnitude of the output voltages produced, the reactive power transfer between the STATCOM and the ac system can be controlled.

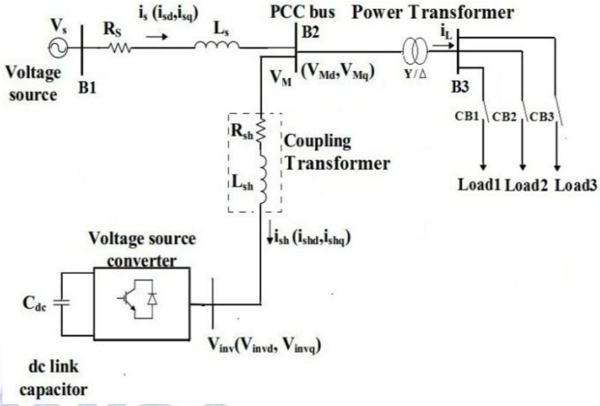



*Fig. 1: Single line diagram of STATACOM*

If the magnitude of the output voltage is greater than the AC system voltage, then the direction of current flow is from STATCOM to the AC system, and the STATCOM injects reactive power into the AC system. This mode of operation is known as capacitive mode of STATCOM. Fig. 2 shows the phasor diagram of capacitive mode of STATCOM.

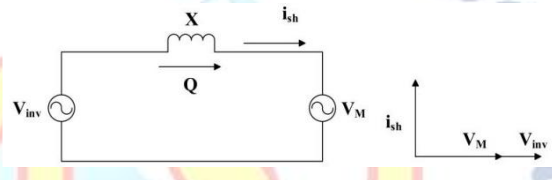



*Fig. 2: Phasor diagram for capacitive operation of STATCOM.*

When the magnitude of the output voltage is lesser than the AC system voltage, then the current flows from the AC system to the STATCOM, and the STATCOM absorbs reactive power from the AC system. This mode is termed as inductive mode of STATCOM. Fig. 3 shows the phasor diagram of inductive mode of STATCOM.

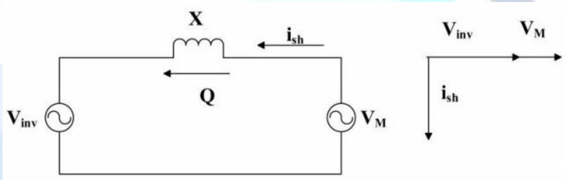



*Fig. 3: Phasor diagram for inductive operation of STATCOM*

When STATCOM voltage is equal to the PCC bus voltage, the reactive power transfer is zero. During such a condition, STATCOM operates in floating mode.

Generally, in converter due to semiconductor Switches losses are occurred, and hence the energy stored in the DC capacitor is utilized for internal losses. Therefore, in order to maintain the DC link voltage at a constant value, the output voltages of the converter are made to lag the AC system voltages by a small angle $\varphi$. In this way the converter absorbs a small amount of real power from the ac system to maintain the capacitor voltage at it required value and replenish its internal losses.

## III. DECOUPLED CURRENT CONTROL STRATEGY

The d-q decoupled current control strategy [10], [11] can be divided in the following sections.

- AC Terminal Voltage controller.
- DC Voltage controller.
- Current controller.

### A. AC terminal voltage regulator

When STATCOM is used in voltage regulation mode, it regulates the PCC bus voltage and maintains its magnitude ($V_{Mag}$) equal to its reference value $V_M^*$.

$$V_{Mag} = \sqrt{V_{Md}^2 + V_{Mq}^2}$$

For this purpose a PI controller is used. The reference value of PCC bus voltage $V_M^*$ and actual PCC bus voltage magnitude $V_{Mag}$ are compared and then the error is given to the PI controller. From this error signal we get reference quadrature axis component of STATCOM current $i_{shq}^*$ which is applied to the inner current loop. When the value of $V_M^*$ is more than $V_{Mag}$, STATCOM injects reactive power so as to increase the value of $V_{Mag}$. When the value of $V_M^*$ is less than $V_{Mag}$, STATCOM absorbs reactive power so as to decrease the value of $V_{Mag}$.

### B. DC voltage regulator

The function of the DC voltage regulator is to maintain the DC voltage, $V_{dc}$, of the STATCOM equal to its reference value, $V_{dc}^*$. A PI (proportional and integral) controller is chosen for DC voltage regulation. The reference value, $V_{dc}^*$, and the actual value, $V_d{}^*{}_c$ are compared and then the error is given to the PI controller. From this error signal we get reference value of d-axis STATCOM current $i_{shd}^*$ which is applied to the inner regulation loop. When value of $V_{dc}$ is less than $V_{dc}^*$, $i_{shd}^*$ rises and a less quantity of active power transfer from the power system to the dc side and $V_{dc}$ rises; and when the value of $V_{dc}$ is more than $V_{dc}^*$, $i_{shd}^*$ reduces and the active power transfer from the power system to the dc side reduces and $V_{dc}$ decreases [10]. This process is continues unless $V_{dc}$ becomes equal to $V_{dc}^*$, hence regulating the dc link voltage $V_{dc}$ at its reference magnitude $V_{dc}^*$.

### C. Current Controller

The reference values of direct and quadrature axis component of STATCOM current i.e. $i_{shd}^*$ and $i_{shq}^*$ are the two inputs for this controller. The differential equations representing the shunt part from the PCC bus to the AC side of the STATCOM are given below.

$$\frac{di_{shd}}{dt} = -\frac{R_{sh}}{L_{sh}} i_{shd} + wi_{shq} + \frac{1}{L_{sh}}[V_{Md} - V_{invd}] \quad (1)$$

$$\frac{di_{shq}}{dt} = -\frac{R_{sh}}{L_{sh}} i_{shq} - wi_{shd} + \frac{1}{L_{sh}}[V_{Mq} - V_{invq}] \quad (2)$$

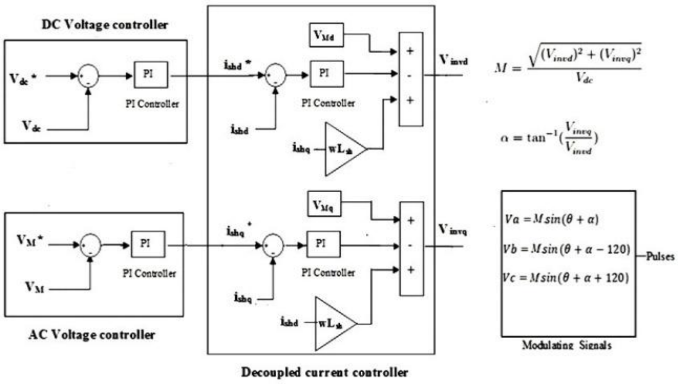



*Fig. 4: d-q decoupled current Control Strategy and Firing Pulses Logic.*

Eq. (1) and (2) show that these two equations are dependent on each other as they include cross coupling terms $\omega I_{shq}$ and $\omega I_{shd}$.

To obtain a decoupled current control, (1) and (2) can be modified as shown below.

$$\frac{di_{shd}}{dt} = -\frac{R_{sh}}{L_{sh}} i_{shd} + x_d \quad (3)$$

$$\frac{di_{shq}}{dt} = -\frac{R_{sh}}{L_{sh}} i_{shq} + x_q \quad (4)$$

where the cross coupled terms are controlled by the control actions $x_d$ and $x_q$.

$$x_d = wi_{shq} + \frac{1}{L_{sh}}[V_{Md} - V_{invd}] \quad (5)$$

$$x_q = -wi_{shd} + \frac{1}{L_{sh}}[V_{Mq} - V_{invq}] \quad (6)$$

So eq. (3) and (4) can be written as

$$\frac{d}{dt}\begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} = \begin{bmatrix} -\frac{Rsh}{Lsh} & 0 \\ 0 & -\frac{Rsh}{Lsh} \end{bmatrix} \begin{bmatrix} i_{shd} \\ i_{shq} \end{bmatrix} + \begin{bmatrix} x_d \\ x_q \end{bmatrix} \quad (7)$$

The control actions $x_d$ and $x_q$ can be expressed as

$$x_d = \left(k_p + \frac{k_I}{s}\right)\left(i_{shd}^{*} - i_{shd}\right) \quad (8)$$

$$x_q = \left(k_p + \frac{k_I}{s}\right)\left(i_{shq}^{*} - i_{shq}\right) \quad (9)$$

where $K_P$ and $K_I$ are gains of proportional plus integral controller.

The direct axis current component $i_{shd}$ maintains the voltage of the dc capacitor to its reference value and the quadrature axis current component $i_{shq}$ plays role in controlling the reactive power of STATCOM or for controlling the PCC bus voltage.

Using following equation we get, $V_{invd}$ and $V_{invq}$,

$$V_{invd} = V_{Md} - K_I(i_{shd}^{*} - i_{shd}) - K_I\int(i_{shd}^{*} - i_{shd})dt + wi_{shq} \quad (10)$$

$$V_{invq} = V_{Mq} - K_I(i_{shq}^{*} - i_{shq}) - K_I\int(i_{shq}^{*} - i_{shq})dt + wi_{shd} \quad (11)$$

From the above equations, we get phase angle and modulation index (M.I) between terminal voltage of the system and STATCOM voltage which are given below,

$$\text{Modulation Index, } M = \frac{\sqrt{(V_{invd})^2 + (V_{invq})^2}}{V_{dc}} \quad (12)$$

$$\propto = \tan^{-1}\left(\frac{V_{invq}}{V_{invd}}\right) \quad (13)$$

Using modulation index (M.I.) and phase angle(Φ),controller generates pulses which are given to the inverter. The d-q decoupled current Control Strategy and Firing Pulses Logic circuit is shown in fig.4

## IV. DIFFERENT STATCOM CONFIGURATIONS

The different STATCOM configuration which are described as below.

### *A. 6 Pulse STATCOM*

A 6 pulse STATCOM is basic STATCOM model. This configuration requires only one bridge for obtaining 6 pulse voltage waveform as output. The output of this bride inverter is applied to 3 phase transformer, which gives is the required system voltage. In 6 pulse STATCOM the output voltage is not sinusoidal because it contains large number of harmonics. The generated output voltage has the harmonics of the order 6n±1 i.e. $5^{th}$, $7^{th}$, $11^{th}$, $13^{th}$ etc. The percentage THD of the STATCOM output voltage is around 15% shown in Fig.5, which does not satisfy the IEEE 519 standard.

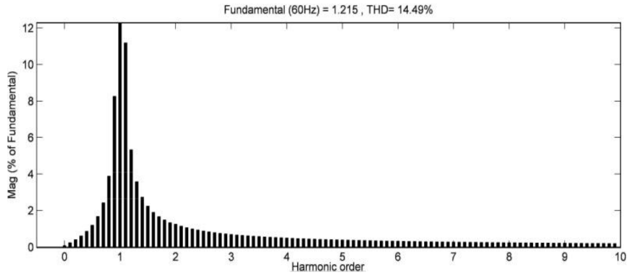



*Fig. 5: Harmonic spectrum of system voltage, $V_M$ for 6 pulse STATCOM obtained from simulation results*

### *B. 12 Pulse STATCOM*

In the 12 pulse STATCOM, two six-pulse converters, having total of six phase-legs are connected in parallel on the same DC bus, and work together as a 12-pulse converter [5]. The two voltages generated by the converters, which have a phase shift of 30°, are applied to the Y-Y and Δ-Y transformers. The combined output voltage has the harmonics of the order 12n ±1 i.e. $11^{th}$, $13^{th}$, $23^{th}$, $25^{t}$ etc. The percentage THD in the STATCOM voltage is around 9%, which is shown in fig.6.

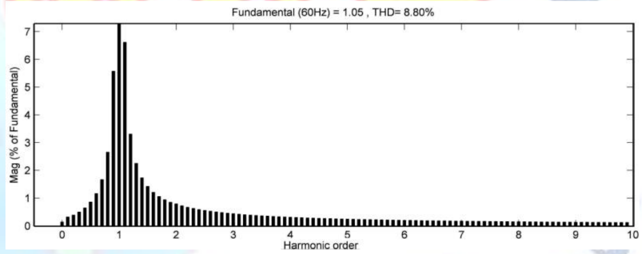



*Fig. 6: Harmonic spectrum of system voltage, $V_M$ for 12 pulse STATCOM obtained from simulation results.*

### *C. 48 Pulse STATCOM*

A 48 pulse STATCOM configuration is achieved by eight transformers, which are connected in series and a phase shift $3.75^0$ is provided between two adjacent 6 pulse converters [12]. In steady state and transient state this configuration gives satisfactory performance. The generated output voltage has the harmonics of the order 48n±1 i.e. $47^{th}$, $49^{th}$ etc. and thus the percentage THD in the voltage is around 4% shown in Fig.7, which satisfies the IEEE 519 standard.

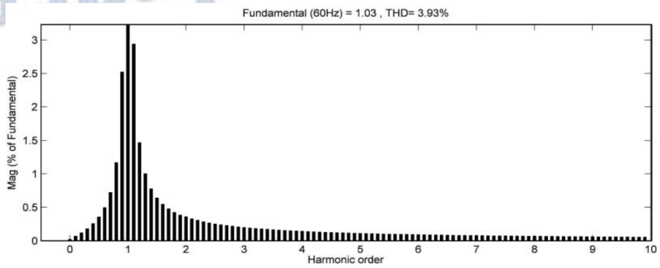



*Fig. 7: Harmonic spectrum of system voltage, $V_M$ for 48 pulse STATCOM obtained from simulation results.*

## V. SIMULATION RESULTS OF 48-PULSE STATCOM

In the given test system three loads are connected at bus B3. Initially system voltage is 1.03 p.u. and capacitor is pre-charged to 2.4 p.u. The parameters of STATCOM are shown in table I.

TABLE I: System Parameters

| **Three Phase AC Source** | | **Load 2** | |
|---|---|---|---|
| Rated Voltage | 236.9[kV] | Active Power | 0.7 [pu] |
| Frequency | 60[Hz] | Reactive Power | 0.5 [pu] |
| S.C.Level | 10000[MVA] | **Load 3** | |
| Base Voltage | 230[kV] | Active Power | 0.6 [pu] |
| Base MVA | 300 | Reactive Power | 0.4 [pu] |
| **Transmission Line** | | **STATCOM** | |
| Resistance,Rs | 0.05[pu] | Primary Voltage | 230[kV] |
| Inductance,Ls | 0.2[pu] | Secondary Voltage | 230[kV] |
| **Power Transformer** | | Nominal Power | 100[MVA] |
| Nominal Power | 300[MVA] | Frequency | 60[Hz] |
| Frequency | 60[Hz] | Eq. Capacitance | 750$\mu$F |
| Prim. Voltage | 230[kV] | **Coupling Transformer** | |
| Sec. Voltage | 33[kV] | Resistance,Rsh | 0.18Ω |
| Magnetization Resistance | 500 | Inductance,Lsh | 0.0374[H] |
| Magnetization Reactance | 500 | **GTO Switches** | |
| **Three Phase Loads** | | Snubber Resistance | 1e5 Ω |
| **Load 1** | | Snubber Capacitance | inf |
| Active Power | 1 [pu] | Internal Resistance | 1e-4 Ω |
| Reactive Power | 0.8 [pu] | No. of Bridge arm | 3 |

The given test system is subjected to different load conditions and simulation results for 6, 12 and 48 pulse STATCOM are given below.

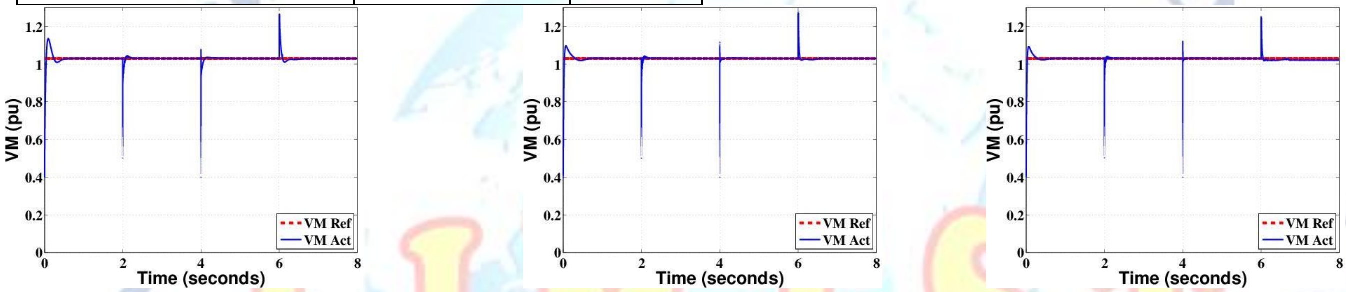



Fig. 8: PCC bus voltage-$V_M$ for 6, 12 and 48 pulse STATCOM respectively.

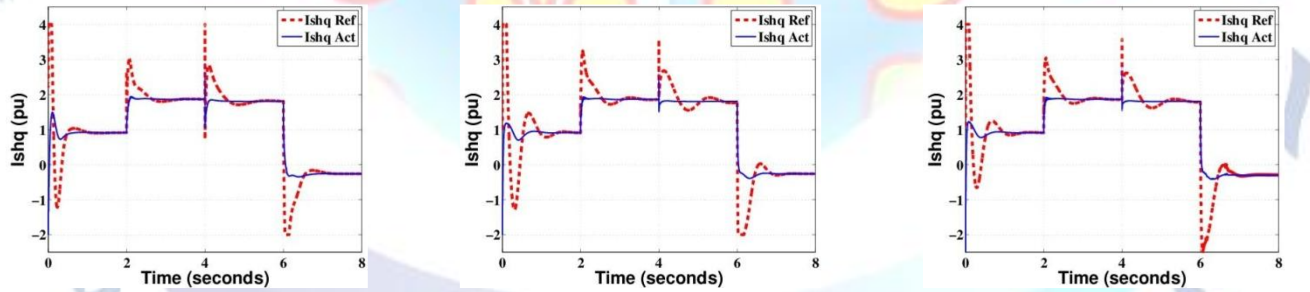



Fig. 9: q-axis STATCOM current-$I_{shq}$ for PI controller of 6, 12 and 48 pulse STATCOM respectively.

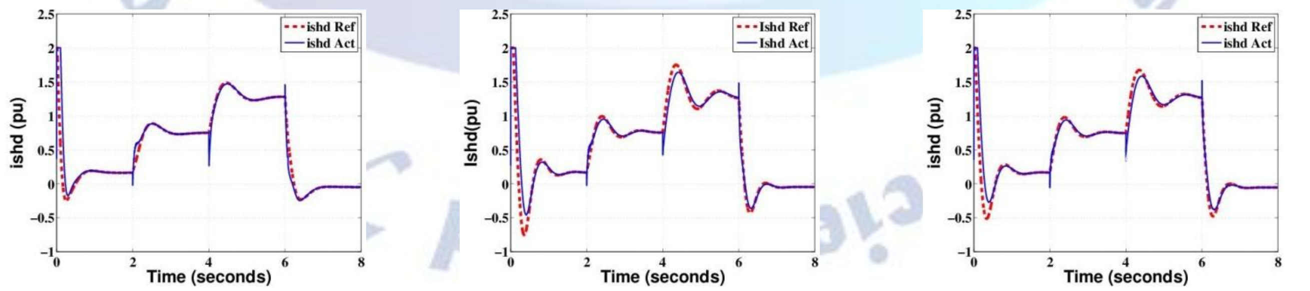
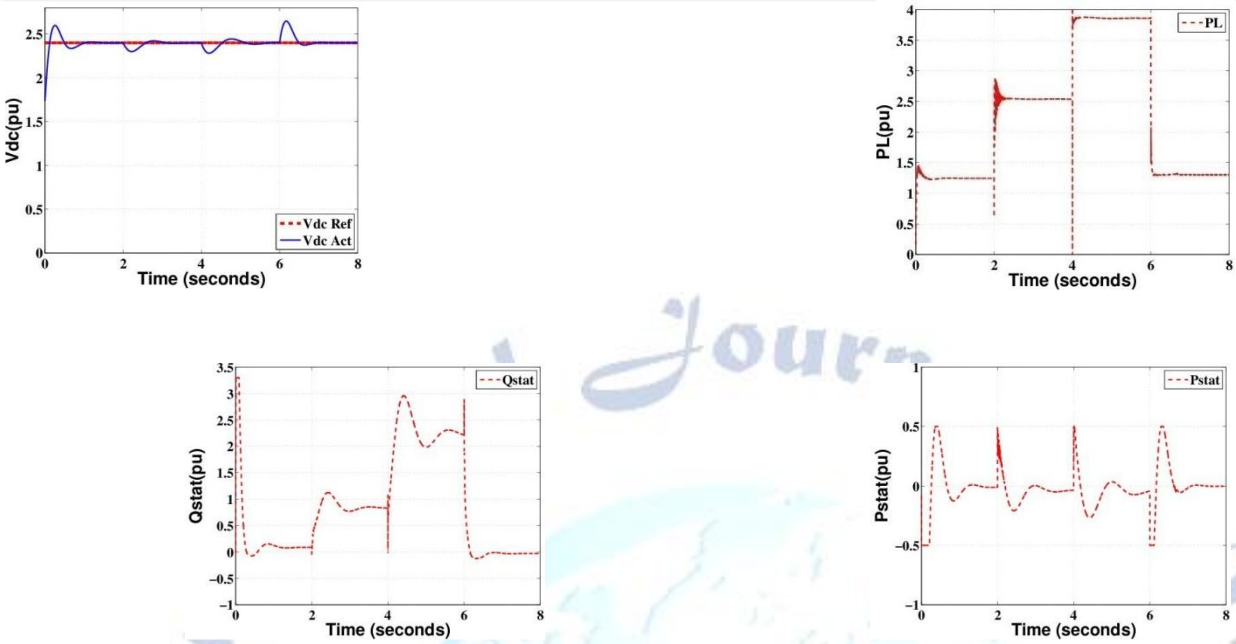



Fig. 10: d-axis STATCOM current-$I_{shd}$ for PI controller of 6, 12 and 48 pulse STATCOM respectively.




a: Dc capacitor voltage-$V_{dc}$ b: Active power of loads-PL

c: Reactive power-$Q_{stat}$ d: Active power-$P_{stat}$

Fig. 11: $V_{dc}$, $P_L$, $Q_{stat}$ and $P_{stat}$ for 48 pulse STATCOM respectively.

**Step 1.** At time t = 0sec, first inductive load(P = 1 p.u. and Q = 0.8 p.u.) is connected. At the same time STATCOM is connected. For maintaining d.c. link voltage constant The STATCOM voltage lags the PCC bus voltage by small angle. Now STATCOM operates in capacitive mode, hence supplies 1.43 p.u. of reactive power to transmission line. The system voltage $V_M$ is maintained at 1.03 p.u. This results in increase in transmitted real power PL=1.24 p.u. to load bus. To overcome switching losses STATCOM absorbs 0.02 p.u. of real power from grid.

**Step 2.** At time t = 2 sec, another inductive load (P = 0.7 p.u and Q = 0.5 p.u.) is also connected. Here both loads are inductive hence reactive power demand of load is also more than previous case. Hence, STATCOM operates in capacitive mode and supplies 3.1 p.u. of reactive power to the grid. The PCC bus voltage $V_M$ is again results in increase in transmitted real power PL=2.54 p.u. to load bus and absorbs 0.045 p.u. of active power from grid.

**Step 3.** At time t=4 sec, capacitive load (P = 0.6 p.u. and Q = 0.4 p.u.) is connected. This capacitive load compensates the inductive load hence STATCOM injects less reactive power in the transmission system. The system voltage $V_M$ is again maintained at 1.03 p.u. The converter draws 0.044 p.u. of real power from grid to overcome inverter losses.

**Step 4.** At time = 6 sec, both inductive loads are removed, only capacitive load (P = 0.6 p.u. and Q = 0.4 p.u.) remains connected. Since, load is capacitive STATCOM operates in inductive mode and absorbs 0.41 p.u. of reactive power from grid. The PCC bus voltage is maintained at 1.03 p.u. Due to voltage regulation PL= 1.39 p.u. of real power is transmitted to load bus.

Above waveforms shows PCC bus voltage $V_M$ (Fig.8), q axis components of STATCOM currents (Fig.9), d axis components of STATCOM currents (Fig.10), and Fig.11 shows dc capacitor voltage and active power of loads, reactive and active power of STATCOM respectively.

## VI. COMPARISION OF RESULTS OBTAINED FROM DIFFERENT STATCOM CONFIGURATIONS

For THD analysis FFT tool is used. From table II, III and IV it is seen that for 48 pulse STATCOM have less THD, peak overshoot and settling time than 6 and 12 pulse STATCOM. Hence we conclude that 48 pulse STATCOM having better performance than 6 and 12 pulse STATCOM. As the number of pulses of STATCOM increases its cost also increases. So, cost of 48 pulse STATCOM is higher than other two configurations.

TABLE II: 6 Pulse STATCOM Results

| System Parameters | | 6 pulse STATCOM Load changes at time(sec) 0 | 2 | 4 | 6 |
|---|---|---|---|---|---|
| STATCOM Voltage $V_{inv}$ | THD | 14.48 | 7.63 | 8.58 | 12.67 |
| | Peak Overshoot | 0.106 | 0.014 | 0.0048 | 0.234 |
| | Settling time | 0.6 | 0.67 | 0.66 | 0.733 |
| STATCOM Current $i_{sh}$ | THD | 13.85 | 12.9 | 9.95 | 14.19 |

TABLE III: 12 Pulse STATCOM Results

| System Parameters | | 12 pulse STATCOM Load changes at time(sec) 0 | 2 | 4 | 6 |
|---|---|---|---|---|---|
| STATCOM Voltage $V_{inv}$ | THD | 8.8 | 6.62 | 6.3 | 8.03 |
| | Peak Overshoot | 0.068 | 0.012 | 0.0045 | 0.245 |
| | Settling time | 0.33 | 0.512 | 0.577 | 0.545 |
| STATCOM current $i_{sh}$ | THD | 10.27 | 8.71 | 8.86 | 12.51 |

TABLE IV: 48 Pulse STATCOM Results.

| System Parameters | | 48 pulse STATCOM Load changes at time(second) 0 | 2 | 4 | 6 |
|---|---|---|---|---|---|
| STATCOM Voltage $V_{inv}$ | THD | 3.93 | 2.1 | 3.85 | 3.56 |
| | Peak Overshoot | 0.063 | 0.01 | 0.002 | 0.12 |
| | Settling time | 0.28 | 0..48 | 0.526 | 0.45 |
| STATCOM current $i_{sh}$ | THD | 6.74 | 7.52 | 8 | 8.04 |

## VII. CONCLUSION

In this paper, for voltage regulation and dynamic power

flow control a 48-pulse ±100 MVA two-level GTO STATCOM has been modeled and simulated using decoupled current control strategy . By varying the modulation index (M) and phase angle (Φ) between PCC bus voltage and STATCOM voltage, voltage regulation at the PCC bus is achieved. The THD and various time response parameters of 6, 12 and 48 pulse STATCOM are compared. The results show that THD of output voltage of 48 pulse STATCOM is less than 5%, which satisfies the IEEE 519 standard. Hence, there is no need of active filter. Also, 48 pulse STATCOM has better transient response as compared to 6, 12 pulse STATCOM.

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