Simulation and Analysis of 48 Pulses STATCOM

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Abstract – *The objective of this paper is to Simulate 48 pulses STATCOM in MATLAB platform for given test system. Implementation of d-q decoupled current control strategy for voltage regulation at point of common coupling control and Compare the results of all STATCOM's on the basis of THD, rise time and peak overshoot etc. As per objectives simulation and analysis of the performance of Static Synchronous Compensator (STATCOM) given in paper, based on 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. D-q decoupled current control strategy is used for implementation of STATCOM. Then 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 48 pulses configurations of STATCOM connected to 230 kV grid has been done using MATLAB/Simulink platform.*

Key Words: Decoupled Current Control System, Voltage Sourced Converter, Total Harmonic Distortion, FACTS and STATCOM.

1. IMPORTANCE OF MODELLING

The switching behavior of power electronics devices leads to complex analysis of STATCOM. Hence, there is a need for simpler and approximate model. Averaging method is one of the common approaches [1]. This method approximates the discontinuous operation of power semiconductor devices into a continuous time model. It simplifies the analysis of system under steady state and transient conditions and speeds up the simulation by avoiding the computation of the switching events in power electronic model. Modeling is preferably done in d-q domain. Application of the d-q transform to balanced three-phase circuits reduces the three phase ac quantities to dc quantities. Simplified calculations can then be carried out on these dc quantities before performing the inverse transform to recover the actual three-phase ac results. It often simplifies calculations and analysis for the control of three-phase inverters. When there is a three phase source, the mutual inductance term arises in transmission lines. This term does not arise when these three phase quantities are transformed into d-q domain. Based on certain assumptions system modeling is carried out. The modeling of a STATCOM is carried out with the following assumptions

a. The source voltages are balanced and sinusoidal.
b. Zero sequence voltages and currents are absent in the system.
c. All switches in the converter are ideal.
d. R_{sh} Represents the losses in the converter and coupling transformer.

1.1 Mathematical Model of abc to dq transformation

In three phase system, supply voltages are given by following equations.

$$V_a = V_{max}\, Sin(\, \omega t + \emptyset\,) \ldots (1)$$
$$V_b = V_{max}\, Sin(\, \omega t + \emptyset - \tfrac{2\pi}{3}) \ldots (2)$$
$$V_c = V_{max}\, Sin(\, \omega t + \emptyset + \tfrac{2\pi}{3}) \ldots (3)$$

For supply currents similar equation are obtained which are written as

$$i_a = i_{max}\, Sin(\, \omega t + \emptyset\,) \ldots (4)$$
$$i_b = i_{max}\, Sin(\, \omega t + \emptyset - \tfrac{2\pi}{3}) \ldots (5)$$
$$i_c = i_{max}\, Sin(\, \omega t + \emptyset + \tfrac{2\pi}{3}) \ldots (6)$$

Here,V_a, V_b, V_c are the three phase supply voltages and i_a, i_b, i_c are the three phase supply currents, V_{max} is the maximum value of supply voltage and φ is the phase angle of supply voltage. These three phase ac voltages and currents are converted into dq rotating reference frame as explained below. In power system abc to dq0 transformation is used to transform the three-phase stationary coordinate system to the dq rotating coordinate system as shown in Fig 1. This transformation is made in two steps:

1. A transformation from the three-phase stationary coordinate system to the two-phase α β stationary coordinate system
2. A transformation from the stationary α β coordinate system to the dq rotating coordinate system

The following equation 7 converts variables from the three phase stationary coordinate system to the dq rotating coordinate system rotating with arbitrary speed.

$$f_{dq0} = T(\emptyset)\, f_{abc}$$

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} sin\emptyset & sin(\emptyset - \frac{2\pi}{3}) & \sin(\emptyset + \frac{2\pi}{3}) \\ cos\emptyset & \cos(\emptyset - \frac{2\pi}{3}) & \cos(\emptyset + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \ldots (7)$$

The inverse transformation from dq0 frame to stationary three phase frame is as follows:

$$f_{abc} = T(\emptyset)^{-1} f_{dq0}$$

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{2}{3}\begin{bmatrix} sin\emptyset & cos\emptyset & 1 \\ sin(\emptyset - \frac{2\pi}{3}) & \cos(\emptyset - \frac{2\pi}{3}) & 1 \\ \sin(\emptyset + \frac{2\pi}{3}) & \cos(\emptyset + \frac{2\pi}{3}) & 1 \end{bmatrix}\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} \ldots (8)$$

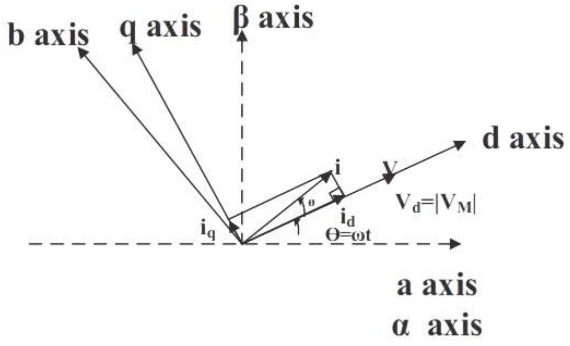


Fig-1: abc to dq transformation

1. α axis is in phase with'a' axis and β is leading α axis by 90º
2. 'd' axis leads α axis by angle ωt at t=0.
3. 'q' axis leads 'd' axis by 90º.
4. 'd' and 'q' axis are rotating in anticlockwise direction at a constant velocity of ω rad/sec, where ω=2πf.

Using this transformation three phase quantities can be converted into two phase dq quantities.

1.2 Analysis of STATCOM

Fig. 2 shows a simplified representation of the STATCOM, including a DC-side capacitor, a converter, and series resistances and inductances in the three lines connecting to the transmission line.

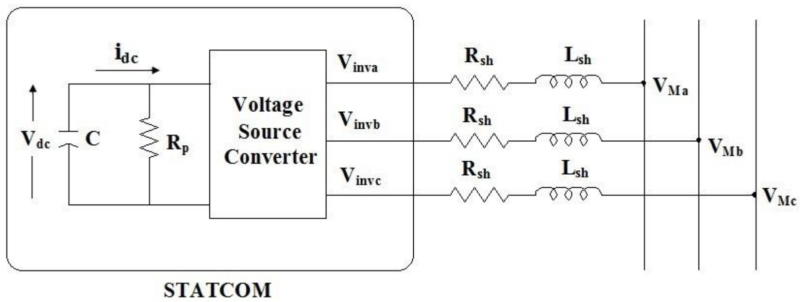


Fig-2: Equivalent circuit of STATCOM

Let, R_{sh} = resistance representing the converter and transformer conduction losses, L_{sh} = inductances representing the leakage inductance of the shunt transformer, R_p = resistance representing the switching losses in the converter, V_{inv} =

converter voltage, V_M = voltage at the point of coupling. The AC side circuit equations from the converter to the PCC bus can be written as follows

$$\frac{d}{dt} i_{sha} = -\frac{R_{sh}}{L_{sh}} i_{sha} + \frac{1}{L_{sh}} [V_{Ma} - V_{inva}] \text{ ..(9)}$$
$$\frac{d}{dt} i_{shb} = -\frac{R_{sh}}{L_{sh}} i_{shb} + \frac{1}{L_{sh}} [V_{Mb} - V_{invb}] \text{ ..(10)}$$
$$\frac{d}{dt} i_{shc} = -\frac{R_{sh}}{L_{sh}} i_{shc} + \frac{1}{L_{sh}} [V_{Mc} - V_{invc}] \text{ ..(11)}$$

Using abc to dq transformation, the above equations can be rewritten in dq domain as shown below.

$$\frac{d}{dt} i_{shd} = -\frac{R_{sh}}{L_{sh}} i_{shd} + \omega i_{shq} + \frac{1}{L_{sh}} [V_{Md} - V_{invshd}] \text{ ..(12)}$$
$$\frac{d}{dt} i_{shq} = -\frac{R_{sh}}{L_{sh}} i_{shq} - \omega i_{shd} + \frac{1}{L_{sh}} [V_{Mq} - V_{incshq}] \text{ ..(13)}$$

The Power balance equation between the dc and ac sides of the converter is given by

$$P_{dc} = P_{ac}$$

Where,

$$P_{dc} = P_{cap} + P_{loss}$$

P_{loss} = power loss due to converter switching.

$$P_{ac} = \frac{3}{2}[\mathrm{V_{invshd}} * \mathrm{i_{shd}} + \mathrm{V_{invshq}} * \mathrm{i_{shq}}]$$

The equation for reactive power of inverter is given by

$$Q = \frac{3}{2}[\mathrm{V_{invshd}} * \mathrm{i_{shd}} - \mathrm{V_{invshq}} * \mathrm{i_{shq}}]$$

2.48 Pulse STATCOM

A 48 pulse STATCOM configuration is achieved by eight transformers, which are connected in series and a phase shift 3.75º is provided between two adjacent 6 pulse converters [2]. In steady state and transient state this configuration gives satisfactory performance. The generated output voltage has the harmonics of the order 48 $n\pm1$ i.e. 47th, 49th etc. and thus the percentage THD in the output voltage is less than 5%, which satisfies the IEEE 519 standard. To obtain 48 pulse STATCOM configurations the simulation diagram and the transformer connections are shown in fig. 3 and fig. 4 For 48 pulse STATCOM PCC bus voltage control is implemented. In this chapter, simulation results of PCC control are presented. The simulation study is carried out for time t = 8 sec.

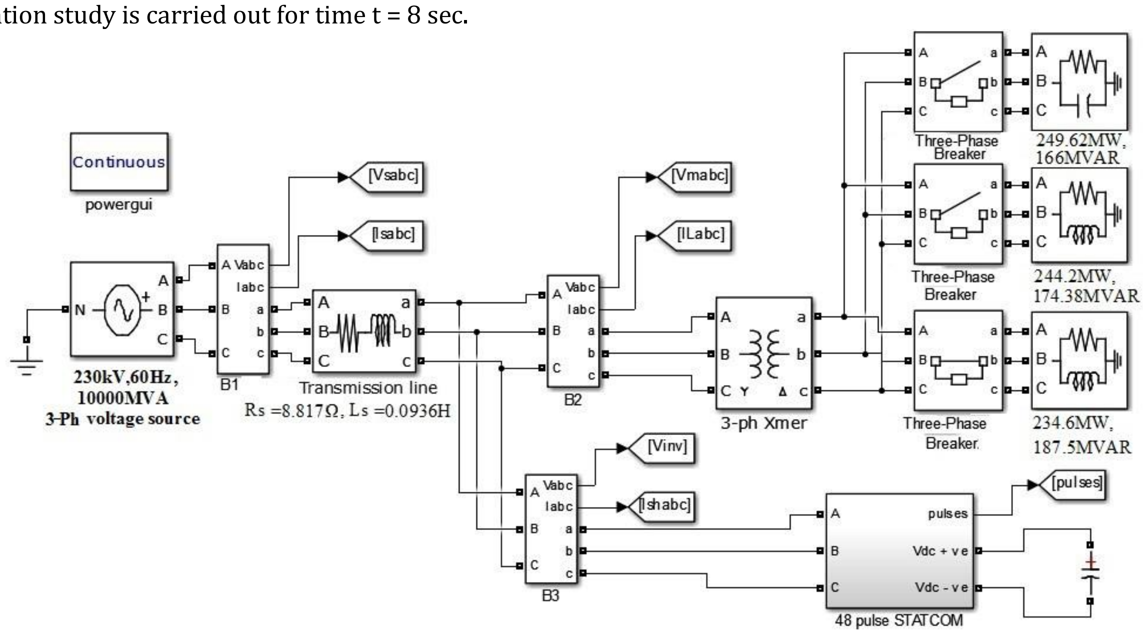


Fig-3: Simulation model of 48 pulse STATCOM

2.1 Simulation Results for 48 pulses STATCOM

The control objectives in this scheme are to maintain dc link capacitor voltage constant and to maintain voltage at PCC bus within limits. By changing the output of VSC, STATCOM draws reactive power to regulate the terminal voltage. V_{dc} And V_M are taken as input signals and their actual value is compared against a reference value to get the error in signals i_{shq} and i_{shd}. These direct and quadrature axis components of shunt current are further fed to controller to get modulation index (M) and phase angle (α). There are four controllers i.e. dc link voltage controller, PCC bus voltage controller, i_{shq} and i_{shd}. This scheme is implemented with the help of PI controllers. Here, simulation study is carried out for 230kV (1.03 p. u.). V_M Ref value is kept close to supply voltage i.e. at 236.9kV (1.03 p. u.) and V_{dc} ref is 552kV (2.4 p. u.). In given test system three loads; load1 (P = 1 p. u. and Q = 0.8 p. u.), load2 (P = 0.7 p. u. and Q = 0.5 p. u.), load3 (P = 0.6 p. u. and Q = 0.4 p. u.) are connected respectively at the interval of every 2 seconds and simulation results for 48 pulse STATCOM is given below.

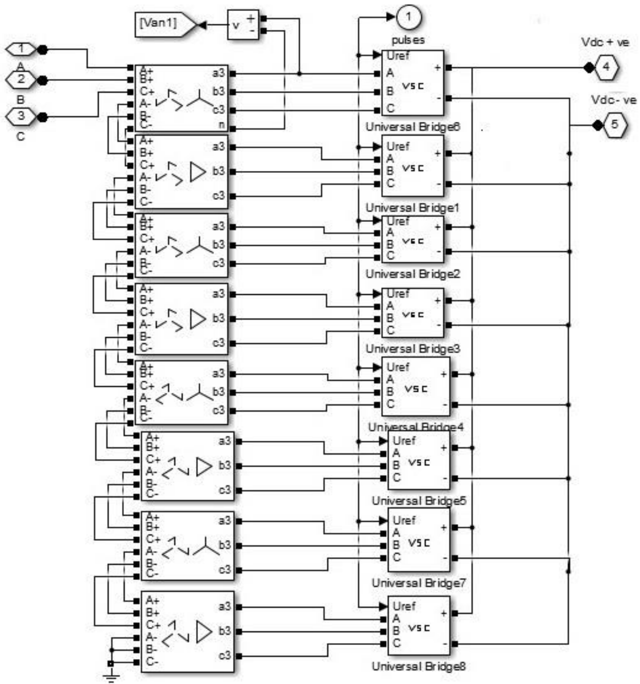


Fig-4: 48 pulse STATCOM configuration

2.2 Analysis at different time intervals

Step 1 At time t = 0 sec, first inductive load (P = 1 p. u. and Q = 0.8 p. u.) is connected. At the same time STATCOM is connected. The STATCOM voltage V_{inv} lags the PCC bus voltage V_M by small angle for maintaining d. c. link voltage constant as Shown in Fig. 5 (b). Since the load is inductive STATCOM operates in capacitive mode and supplies 1.43 p. u. of reactive power to transmission line as shown in as shown in Fig. 5 (g). The PCC bus voltage V_M is maintained at 1.03 p. u. which as Shown in Fig. 5 (a). The d-axis component of STATCOM current is associated with charging of capacitor. Increase in load reduces the PCC bus voltage, so inverter output voltage has to be increased. This causes reduction in d. c. capacitor voltage. So in order to maintain d. c. capacitor voltage constant, i_{shd} increases as Shown in Fig. 5 (c). When increase in load causes reduction in PCC bus voltage, so to maintain PCC bus voltage constant i_{shq} increases as Shown in Fig. 5 (d). Since PCC bus voltage is to be maintained constant the active and reactive power supplied to the load increases as Shown in Fig. 5 (e & f). respectively. This voltage regulation results in increase in transmitted real power PL = 1:25 p. u. to load bus as Shown in Fig. 5 (e). To overcome switching losses STATCOM absorbs 0.02 p. u. of real power from ac power system as Shown in Fig. 5 (h).

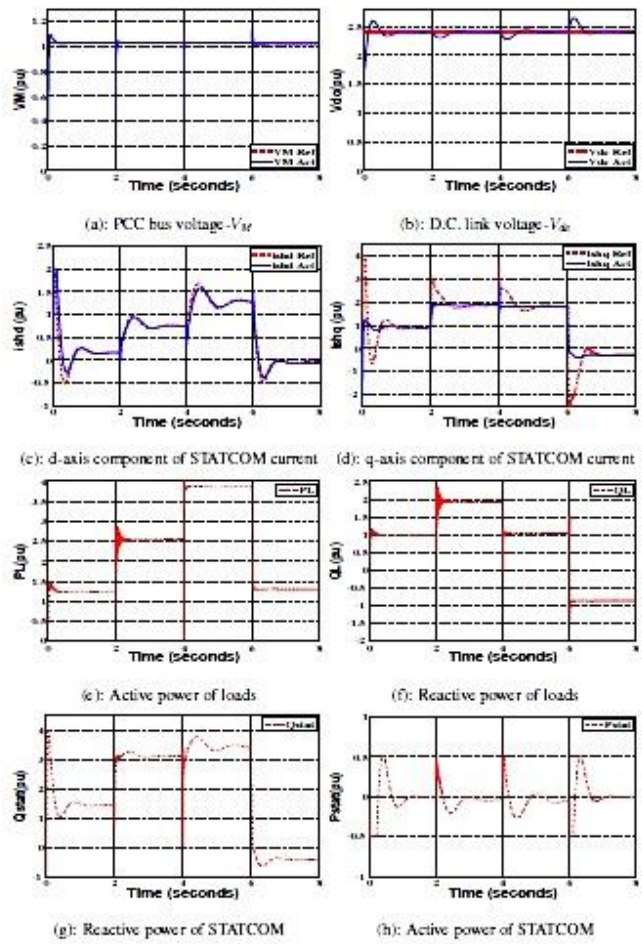
Step 2 At time t = 2 sec, another inductive load (P = 0.7 p. u and Q = 0.5 p. u.) is connected. Here both loads are inductive hence reactive power demand of load is also more than previous case. Hence, STATCOM operates in capacitive mode and injects 3.1 p. u. of reactive power in transmission line as Shown in Fig. 5 (g). The PCC bus voltage V_M is again maintained at 1.03 p. u. which as Shown in Fig. 5 (a). This voltage regulation results in increase in transmitted real power PL = 2:54 p. u. to load bus as Shown in Fig. 5 (e). The STATCOM absorbs 0.045 p. u. of active power from power system to compensate additional losses as Shown in Fig. 5 (h).

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 PCC bus voltage V_M is again maintained at 1.03 p. u. which as Shown in Fig. 5 (a). The converter draws 0.044 p. u. of real power from power system to overcome inverter losses as Shown in Fig. 5 (h).

Step 4 At time = 6 sec, both inductive loads are disconnected, only capacitive load (P = 0.6 p. u. and Q = 0.4 p. u.) remains connected. Thus, due to capacitive load, voltage at the load bus B2 increases above its reference value. Since load is capacitive STATCOM operates in inductive mode and absorbs 0.41 p. u. of reactive power from transmission line as Shown in Fig. 5 (g). The PCC bus voltage V_M is maintained at 1.03 p. u .which is shown in as Shown in Fig. 5 (a). Due to voltage regulation PL = 1:3 p. u. of real power is transmitted to load bus as Shown in Fig. 5 (e).

2.3 Analysis of Voltage and current harmonics

Harmonic spectrum of STATCOM voltage and current at different load conditions are summarized in table 1 below with comment.



(a): PCC bus voltage -V_M (b): D.C. link voltage -V_{dc}
(c): d-axis component of STATCOM current (d): q-axis component of STATCOM current
(e): Active power of loads (f): Reactive power of loads
(g): Reactive power of STATCOM (h): Active power of STATCOM

Fig-5: 48 pulse STATCOM configuration

Table -1: THD Analysis of Voltage and current

System Parameters		48 pulse STATCOM			
		only load 1 (P = 1 and Q =0.8) is connected.	when load 1 (P = 1 and Q =0.8) and load 2 (P = 0.7 and Q =0.5) are connected.	when load 1 (P = 1 and Q =0.8), load 2 (P = 0.7 and Q =0.5) and load3 (P = 0.6 and Q =0.4) are connected	when only load 3 (P = .6 and Q =0.4) remains connected
STATCOM Voltage (V_{inv})	THD	3.93%	2.1%	3.85%	3.56%
STATCOM current (i_{sh})	THD	7.53%	6.71%	8%	8.04%
Comment		As harmonic order increases the magnitude of harmonics is reduced	After 3rd harmonic the magnitude of harmonics negligible.	After 3rd harmonic order the magnitude of harmonics is reduced	As harmonic order increases, the magnitude of harmonics is reduced and after 5th harmonic, it is negligible

Also analysis of peak overshoot, settling time of STATCOM voltage are done for 48 pulses STATCOM and the values obtained during different load conditions are tabulated in Table- 5.1. At t= 0 sec, when load 1 is connected, the STATCOM voltage is subjected to 0.063 p. u. overshoot with settling time of 0.28 seconds. After connecting load 2 at t = 2 sec, overshoot and settling time for STATCOM voltage are 0.01 p. u. and 0.48 seconds respectively. Switching in load 3 at t=6 sec, results in 0.002 p. u. overshoot and 0.526 seconds settling time. At t = 8 sec, hence load 1 and 2 are disconnected and only load 3 remains connected, this results in 0.12 p. u. overshoot with settling time of 0.45 seconds.

Table -2: 48 Pulse STATCOM Results

System Parameters		48 pulse STATCOM			
		Load changes at time(sec)			
		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	7.53	6.71	8	8.4

Table -3: Comparison of Results Obtained From Different STATCOM Configurations

System Parameters		6 pulse STATCOM				12 pulse STATCOM				48 pulse STATCOM			
		Load changes at time(sec)				Load changes at time(sec)				Load changes at time(sec)			
		0	2	4	6	0	2	4	6	0	2	4	6
STATCOM Voltage (V_{inv})	THD	14.48	7.63	8.58	12.67	8.8	6.62	6.3	8.03	3.93	2.1	3.85	3.56
	Peak Overshoot	0.106	0.014	0.0048	0.234	0.068	0.012	0.0045	0.245	0.063	0.01	0.002	0.12
	Settling time	0.6	0.67	0.66	0.733	0.33	0.512	0.577	0.545	0.28	0.48	0.526	0.45
STATCOM current (i_{sh})	THD	13.85	11.31	12.51	14.27	10.27	8.62	8.84	12.2	7.53	6.71	8	8.4

2.4 Overview of Results of 48 pulse STATCOM

1. 48 pulse STATCOM is used for voltage regulation of PCC bus voltage.
2. The generated output voltage has the harmonics of the order 48n_ 1 i.e. 47th, 49th etc. and thus the percentage THD in the output voltage is less than 5%, which satisfies the IEEE 519 standard.
3. THD of output voltage ranges from 2.1-3.93%.
4. THD of output current ranges from 6.71-8.04%.
5. Peak overshoot of output voltage ranges from 0.002-.12 p. u.
6. Settling time of output voltage ranges from 0.28-0.524 seconds.

3. CONCLUSIONS

By varying the modulation index M and phase angle α between PCC bus voltage and STATCOM voltage, voltage regulation at the PCC bus is obtained. Comparison of 6, 12 and 48 pulse T-STATCOM is done for THD, peak overshoot and settling time of PCC bus voltage and current. This decoupled current control scheme is used to control the real power (to maintain the dc-link voltage) and required reactive power. By using d-q decoupled current control strategy, we can control I_{shd} and I_{shq} independently. THD of output voltage for 48 pulses STATCOM is less than 5%, which satisfies the IEEE 519 standard. Hence, there is no need of active filter. THD, peak overshoot and settling time for 48 pulses STATCOM is less than 6 and 12 pulse STATCOM. Hence, transient response of 48 pulses STATCOM is better than 6 and 12 pulses STATCOM.

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