

Performance Comparison of Star Connected Cascaded STATCOM Using Different PWM Techniques

Ch. Lokeshwar Reddy¹, P. Satish Kumar², M. Sushama³

¹Department of EEE, CVR College of Engineering, Hyderabad, India

²Department of Electrical Engineering, University College of Engineering, Osmania University, Hyderabad, India

³Department of EEE, JNTU College of Engineering, Hyderabad, India

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ABSTRACT

Five control algorithms are presented in this paper for STATCOM that meets the requirement of load reactive power and correspondingly voltage balancing of isolated dc capacitors for H-bridges. The control techniques used for an inverter in this paper are Sinusoidal Phase Shifted Carrier (SPSC) PWM, Sinusoidal Phase Disposition (SPD) PWM Third Harmonic Injected Phase Shifted Carrier (THIPSC) PWM, Space Vector Phase Shifted Carrier (SVPSC) PWM, and Space Vector Phase Disposition (SVPD) PWM techniques. The STATCOM performance for the different load changes is simulated in MATLAB environment. The performance parameters such as balancing the DC link voltage, THD for the STATCOM output currents, voltages, and reactive components supplied by the STATCOM to the load are compared for all the control strategies.

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Corresponding Author:

Ch. Lokeshwar Reddy,

Department of EEE, CVR College of Engineering, Hyderabad, India

Email: reddy.lokeshwar@gmail.com

1. INTRODUCTION

Recently, attention towards electric power quality has enhanced due to more preventive guidelines on this area. This interest has led to the development of multiple equipment, which could progress the energy transmission ability and quality of the voltage in the connection point. These innovative devices are popular as Flexible AC Transmission System (FACTS), which are inventions of modern-power electronics. Considerable work has been carried out using these FACTS devices for high-voltage transmission [1]-[2]. Innumerable FACTS devices, like Static Synchronous Compensators (STATCOMs), Static Synchronous Series Compensators (SSSCs), and Unified Power-Flow Controllers (UPFCs) are extensively used in power systems because of their capability to stabilize power transmission systems and to improve power quality in distribution systems. STATCOM technology is progressively employed to increase power transfer capability and improve voltage stability [3].

A STATCOM is fundamentally one of the shunt-type FACTS device. STATCOM consists of one inverter with energy storing capacitors on its dc side, control system, and it is connected in parallel with the grid. The STATCOM controls the reactive-power flow in the electric line, either by injecting or absorbing it. This reactive-power output of the STATCOM is controlled by changing the amplitude of the output voltage [4].

The development of present power semiconductor switches (GTO, IGBT) and the evolution of new switching devices (IGCT, IEGT, etc.), collective with the utilization of novel inverter topologies, have permissible the increase of power and voltage ratings of the electronic converters. This means that, in few cases, the inverter can be directly connected to medium voltage levels without coupling transformer [5]. Multilevel converters have been used widely for STATCOM as it can improve the power rating of the compensator, to make it appropriate for medium or high-voltage bulk power applications [6]-[7]. There are

many types of multilevel converter topologies used for implementing STATCOMs such as diode-clamped converter, flying capacitor based converter, and cascaded H-bridge converter. Cascaded H-bridge topology is widely employed because of its several advantages: (1) it can produce nearly sinusoidal voltage waveform and diminishes harmonics (2) it can respond faster because of removing the necessity of transformer to provide the necessary voltage levels (3) modularized circuit design and construction is very easy due to simplicity of configuration [8]-[10].

Now days the cascaded H-bridge converters in each phase is replacing many other configurations for a three-phase medium-voltage multilevel conversion system [11]-[12]. This multilevel converter or inverter has been considered as an alternative to a three-level diode-clamped converter or inverter [13] for STATCOM and variable-speed drive applications.

When the multilevel converter is employed to STATCOM, each of the cascaded H-bridge converters should be furnished with an electrically isolated and floating dc capacitor without any source in the circuit. This allows eliminating a bulky and expensive line-frequency transformer from the cascade STATCOM. For instance, the weight of a three-phase line-frequency transformer rated at 6.6 kV and 1 MVA weights from 3000 to 4000 kg, whereas the weight of the three-phase cascaded converters with the same rating may weights from 1000 to 2000 kg [14].

The problem associated with cascade STATCOM is unequal voltage distribution between the multiple floating dc capacitors. Improper conduction of switching devices, switching losses produced by semiconductor devices used in the circuit, as well as signal disparity and resolution issues inherent in the control circuit and presence of voltage/current sensors, may results into voltage imbalance to the dc capacitors.

The converter used in STATCOM acts as an inverter and each H-bridge cell can produce three different voltage levels of output with the control of four switches. The control of the phase angle between line voltage and the voltages generated by inverter, results STATCOM to absorb or supply reactive power to the load. The power drawn from the dc source should maintained equal for a cascaded H-bridge based STATCOM. Therefore, each H-bridge cell in the inverter is equally operated. But, due to the semiconductor devices of the inverter are not ideal and have dissimilar tolerance errors, each DC capacitor voltage may not be accurately balancing. It is the main drawback for cascaded H-bridge converters employed for STATCOM, so it is essential using an extra control strategy to balance the DC-link voltages [15]-[18].

Numerous literatures have deliberated how to balance the DC voltage of the cascaded H-bridge multilevel converter. The individual balancing control is combined with clustered balancing control for regulating DC-link voltage [19]. But, assigning appropriate values to gain parameters is not easy [19]

2. MODULATION STRATEGIES

Based on voltage control Cascade STATCOMs can be classified as staircase modulation and pulse width modulation (PWM). More Research has been carried out in [18], [20]-[21] about the staircase modulation and PWM. Mostly PWM is chosen when a transformerless cascaded STATCOM is used. The foremost reason is that the 1.7 kV trench-gate insulated-gate bipolar transistors (IGBTs) can be functioned at a switching frequency more than 1 kHz with a less switching losses. PWM is superior for dynamic performance, more robust for line disturbances and faults, and more flexible in applications associated to staircase modulation.

2.1. Sinusoidal Pulse Width Modulation

Modulation process for multilevel inverters are based on carrier arrangements. The carriers shifted by horizontally is Phase Shifted Carrier PWM (SPSCPWM). Figure 1 shows the arrangement of carrier and reference signals for the SPSCPWM technique. Mostly phase shifted carrier PWM is chosen for the cascaded multilevel inverters, it results an evenly power distribution among all cells and it is very easy to implement separately for the number of inverters. The PSCPWM technique results in the termination of all carrier and connected sideband harmonics up to $2N$ th carrier group, where N is the number of H-bridges in each phase.

The Phase-shifted unipolar sinusoidal PWM with a carrier frequency of 1.2 kHz is applied to a cluster of two cascaded H-bridge converters in each phase. Then, the ac voltage of each cluster has a 5-level line-to-neutral PWM waveform with the lowest harmonic sideband centered at 4.8 kHz ($= 1.2\text{KHz} \times 2 \times 2$).

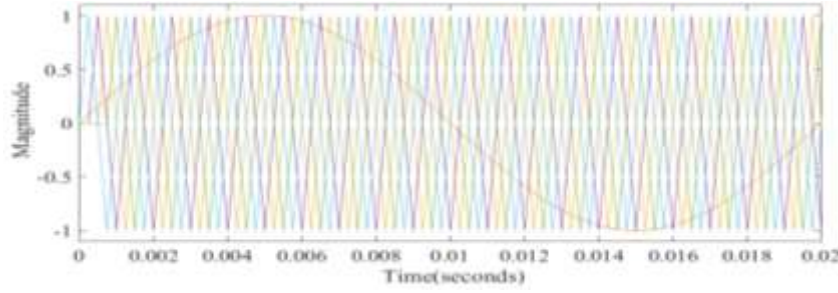


Figure 1. Carrier and reference waveform arrangements for a five level STATCOM with Sinusoidal Phase Shifted Carrier strategy

2.2. Modified Carrier-Based SVPWM

In the conventional SVPWM technique the mapping of the outer sectors to an inner sub hexagon sector should be done to determine the switching time period for multilevel inverters. The switching vectors corresponding to the present sectors are switched and the time periods calculated from the mapped inner sectors. Because of the presence of more number of sectors and inverter sectors realizing this technique will be tough in multilevel inverters. And computation time is increased in this method during real time applications.

Before comparing with carrier signals, sinusoidal references are added with appropriate offset voltage to get the performance of SVPWM in the carrier based PWM technique [22]-[23]. The finding of offset voltage is contingent on modulus function which depends on the DC-link voltage, the number of levels and the phase voltage magnitudes.

A shortened method is presented, where correct offset times are find for centering the time periods of middle inverter vectors in a sampling interval. A technique is given in [24] for finding the maximum likely peak amplitude of the fundamental phase voltage in the linear modulation. The subsequent equations are used to compute offset time T_{offset} .

$$T_a = \frac{V_a * T_s}{V_{dc}} \quad (1)$$

$$T_b = \frac{V_b * T_s}{V_{dc}} \quad (2)$$

$$T_c = \frac{V_c * T_s}{V_{dc}} \quad (3)$$

Here T_a , T_b and T_c are the time periods of imaginary switching, relative to the instantaneous values of the reference phase voltages V_a , V_b and V_c and T_s is the sampling time period.

$$T_{offset} = \left[\frac{T_0}{2} - T_{min} \right] \quad (4)$$

$$T_0 = [T_s - T_{effect}] \quad (5)$$

$$T_{effect} = T_{max} - T_{min} \quad (6)$$

T_{max} = Maximum magnitude of the three reference phase voltages, in a sampling interval.

T_{min} = Minimum magnitude of the three reference phase voltages, in a sampling interval.

The inverter switching vectors are centered in a sampling period by the accumulation of offset voltage to the reference phase voltages that equate the performance of SPWM technique with the SVPWM technique. This projected SVPWM signal generation does not include look up table, sector identification, angle information and space vector voltage amplitude measurement for switching vector determination as required in the conventional multilevel SVPWM technique. This technique is further effective when compared to conventional multilevel SVPWM technique. Figure 2 shows the produced there-phase reference

waveforms with the modified SVPWM technique. The generated reference waveforms are compared with triangular carrier signals to produce switching pulses for the switching devices. Figure 3 shows the arrangement of carrier and reference waves for the modified Space Vector Phase Shifted Carrier PWM technique.

The modulation index of a three-phase inverter system can be increased by including a common mode third-harmonic term into the fundamental reference waveform of each phase. This third harmonic component does not affect the line to line fundamental output voltage, since the common voltages cancel between the phase legs, but it reduces the peak size of the envelope of each phase leg voltage. Hence, the modulation index can be increased without moving into over modulation.

To maximize the reference waveforms, the magnitude of third harmonic injected signal is 1/6 and to increase the output fundamental component, the magnitude of fundamental reference waveform is 1.15. Figure 4 shows the carrier and reference waveform arrangement for the Third Harmonic Injected Phase Shifted Carrier (THIPSC) strategy. The reference voltages for THIPSC are

$$V_a(t) = 1.15\sin(\omega t) + (1/6)\sin(3\omega t) \quad (7)$$

$$V_b(t) = 1.15\sin(\omega t - 2\pi/3) + (1/6)\sin(3\omega t) \quad (8)$$

$$V_c(t) = 1.15\sin(\omega t - 4\pi/3) + (1/6)\sin(3\omega t) \quad (9)$$

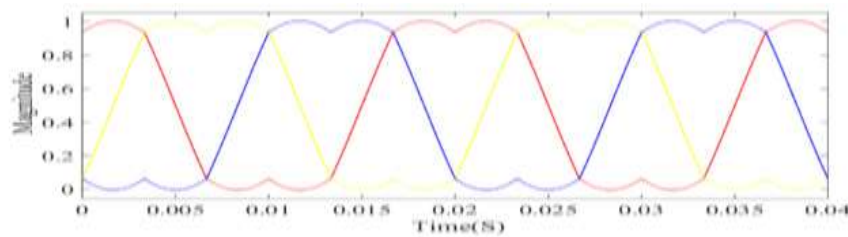


Figure 2. Reference signals for Modified SVPWM

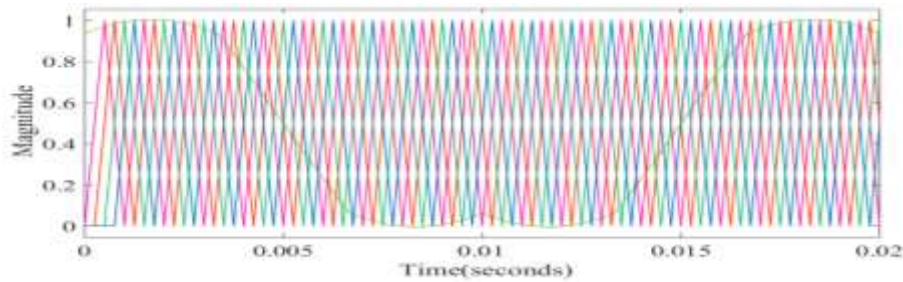


Figure 3. Carrier and reference waveform arrangements for a five level STATCOM with Space Vector Phase Shifted Carrier strategy

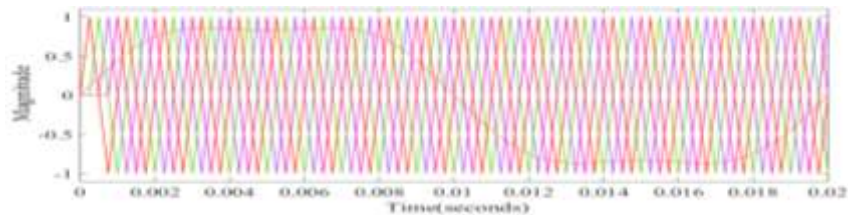


Figure 4. Carrier and reference waveform arrangements for a five level STATCOM with Third Harmonic Injected Phase Shifted Carrier strategy

3. CONTROL STRATEGY FOR CASCADED FIVE LEVEL INVERTER BASED STATCOM

The five-level cascaded H-bridge multilevel STATCOM is shown in Figure 5. This STATCOM consisting of cascaded five-level inverter, which is connected through coupling reactors to the grid. In this topology two single phase H-bridge inverter cells with capacitors as dc-link are connected in series to generate five levels of phase voltage. The levels in phase voltage are $2N+1$, where N is single phase inverter cells present in a phase and the number of levels in line voltage is $2m-1$, where m is the number of levels in phase voltage.

In the design of STATCOM, the three phase quantities $v_a, v_b, v_c, i_{al}, i_{bl}, i_{cl}, i_{as}, i_{bs}$ and i_{cs} are source voltages, load currents and inverter currents, these are transformed in to $v_d, v_q, i_{dl}^*, i_q^*, i_d$ and i_q in the synchronously rotating reference frame. The mathematical model of the cascaded inverter is transformed to the stationary rotating reference frame. Figure 6 shows the control block diagram for the generation of reference voltages for various control techniques. The d - q axes reference voltage components of the inverter e_d and e_q are controlled as

$$e_d = x_1 + v_d - \omega L i_q \quad (10)$$

$$e_q = x_2 + \omega L i_d \quad (11)$$

Where v_d is the direct axis component of source voltage and i_d, i_q, i_{dl}^* and i_q^* are d-q axes current components of the inverter and load respectively. The synchronously rotating frame and source voltage vector are aligned together so that the q-component of the source voltage v_q is made zero. The control parameters x_1 and x_2 are controlled as

$$x_1 = (k_{p2} + \frac{k_{i2}}{s})(i_d^* - i_d) \quad (12)$$

$$x_2 = (k_{p3} + \frac{k_{i3}}{s})(i_q^* - i_q) \quad (13)$$

The d-axis reference current i_d^* is

$$i_d^* = (k_{p1} + \frac{k_{i1}}{s})[(V_{dc}^*) - (V_{dc1} + V_{dc2} + V_{dc3} + V_{dc4} + V_{dc5})] \quad (14)$$

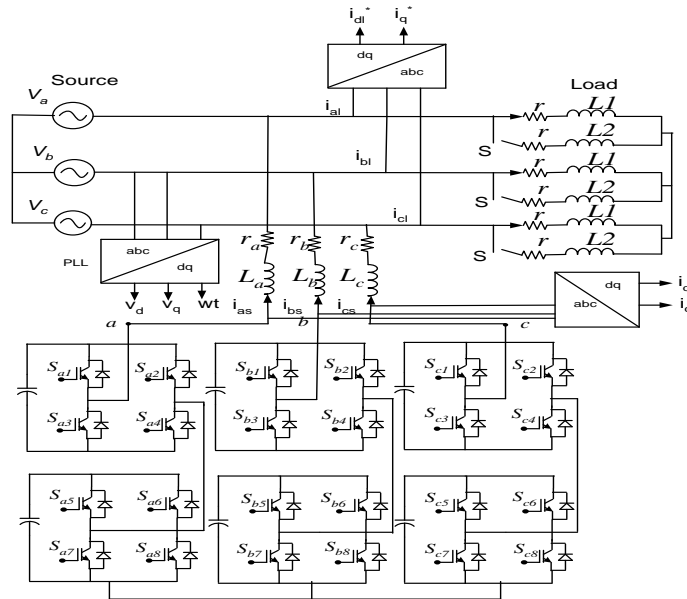


Figure 5. Cascaded multilevel STATCOM

$$e_{ds} = (\cos\omega t)e_d + (\sin\omega t)e_q \quad (15)$$

$$e_{qs} = -(\sin\omega t)e_d + (\cos\omega t)e_q \quad (16)$$

$$v_{ar} = e_{ds} \quad (17)$$

$$v_{br} = -\frac{1}{2}e_{ds} + \frac{\sqrt{3}}{2}e_{qs} \quad (18)$$

$$v_{cr} = -\frac{I}{2}e_{ds} - \frac{\sqrt{3}}{2}e_{qs} \quad (19)$$

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4. SIMULATION RESULTS

The five level Cascaded Multilevel STATCOM is considered for simulation. The simulation of STATCOM is carried out using MATLAB/SIMULINK for different load changes. The inverter is controlled by using Sinusoidal Phase Shifted Carrier (SPSC) PWM, Sinusoidal Phase Disposition (SPD) PWM, Third Harmonic Injected Phase Shifted Carrier (THIPSC) PWM, Space Vector Phase Shifted Carrier (SVPSC) PWM, and Space Vector Phase Disposition (SVPD) PWM techniques. The system parameters and PI controller parameters for voltage control, current control loops are shown in Table 1 and Table 2 respectively.

Figures 7 and 8 shows the response of STATCOM for various performance parameters such as harmonic analysis of output voltage and current of STATCOM, balancing the DC-link voltages for all H-bridges, Ripple content in DC-link voltage, comparison of reactive components required by the load and supplied by the STATCOM, and Phasor relations between Source voltage and STATCOM current for the variation of load from RL to RC at 1 sec by using SPSCPWM and SPDPWM techniques respectively. It is observed that the STATCOM works perfectly for a reference DC link voltage of 1500 V, this voltage is equally distributed among all the H-bridge DC-link capacitors and it is observed that balanced for all types of load changes. If the load is changed suddenly also STATCOM supplies reactive components required by load.

It is observed from the Figure 7 with the use of SPSCPWM technique, the ripple content in the DC-link voltage is low and it is around 9V. The harmonics in the output current is in the order of 3 % and in the voltage, is 26.31%. No harmonics observed below 4.8 kHz frequency due to SPSCPWM technique. During the change of load from RL to RC the STATCOM currents is changed from lagging to leading with respect to source voltage. After changing the load from inductive to capacitive at 1 sec, the reactive components supplied by the STATCOM changed from negative to positive, but to reach steady state it takes up to 3 sec.

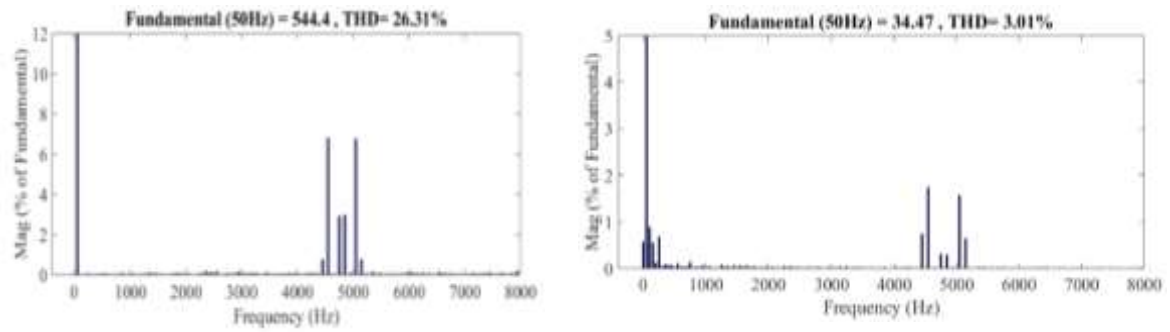
Table 1. Simulation System Parameters

Supply Voltage	415 V RMS(Phase-Phase)
DC link voltage	250 V for all control techniques
Load Parameters	R = 4.6 Ω , L = 12.4 mH R = 4.6 Ω , L = 5.01 mH(for half load)
DC link capacitance	10 mF
Fundamental frequency	50 Hz
Switching frequency	1200 Hz
STATCOM Interfacing resistance	0.13 Ω
STATCOM Interfacing Inductance	2.19e-3 H

Table 2. Parameters of PI Controllers

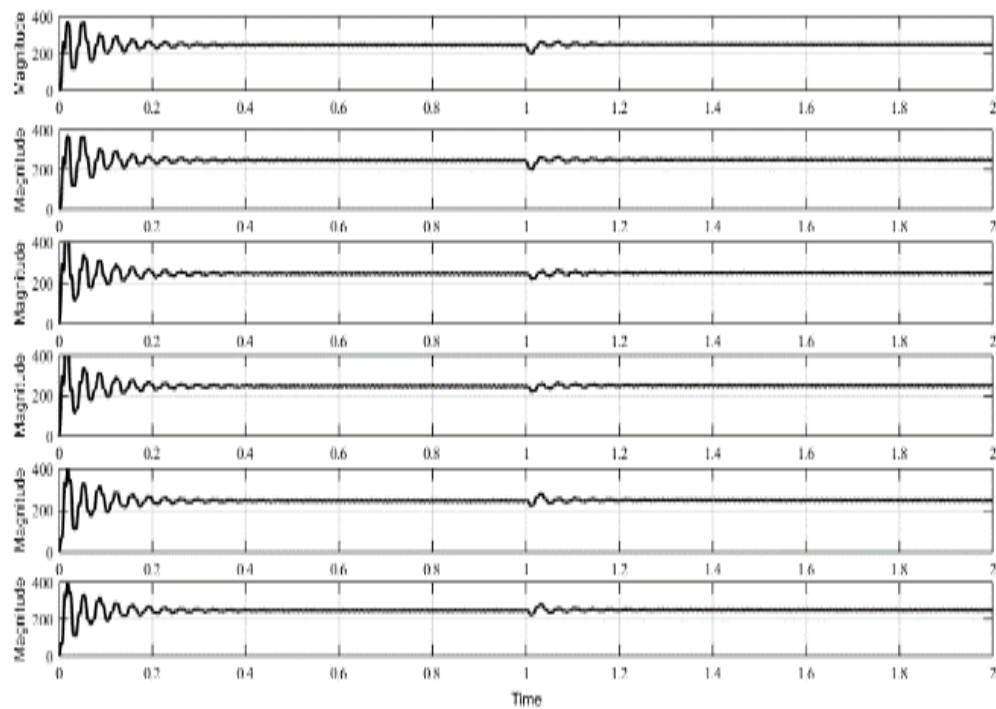
PI Controller	Control Variable	Proportional Gain	Integral Gain
PID1	Voltage	0.07	0.2
PID2	Voltage	0.08	0.2
PID3	Current	4	6

It is observed from the Figure 8 with the use of SPDPWM technique, the ripple content in the DC-link voltage is high and it is around 30V. The harmonics in the output current is in the order of 12.09 % and in the voltage, is 24.67%. During the change of load from RL to RC the STATCOM currents is changed from lagging to leading with respect to source voltage. After changing the load from inductive to capacitive at 1 sec, the reactive components supplied by the STATCOM changed from negative to positive, but to reach steady state it takes up to 3.5 sec and the ripple content in the STATCOM reactive current component is high.

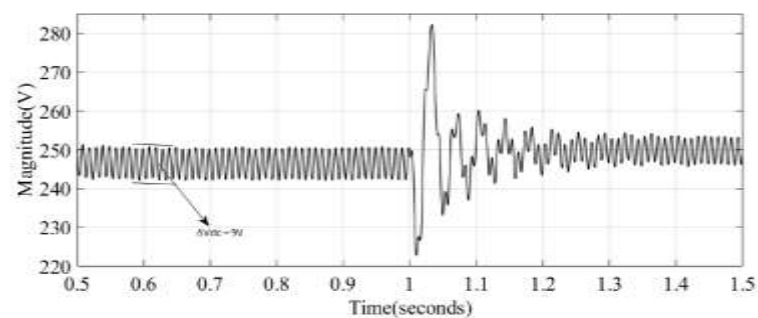


a. Harmonic analysis of STATCOM output voltage

b. Harmonic analysis of STATCOM output current

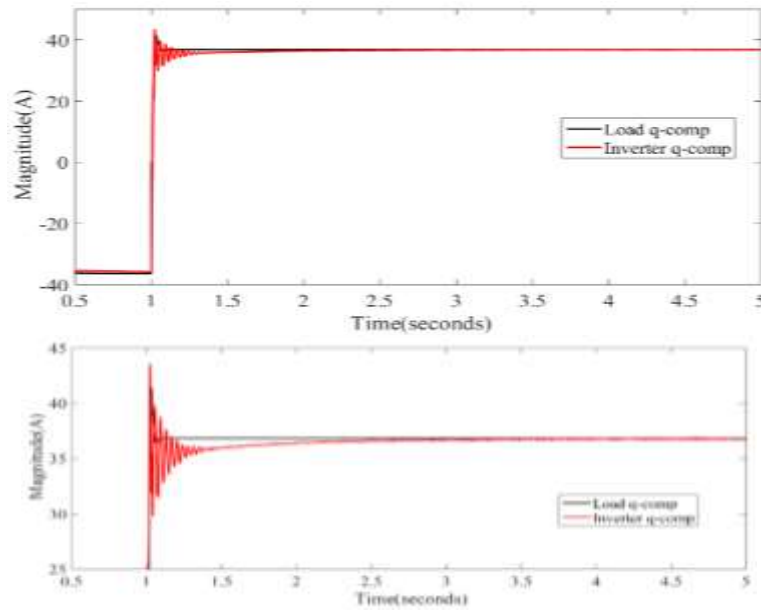


c. DC Link voltages



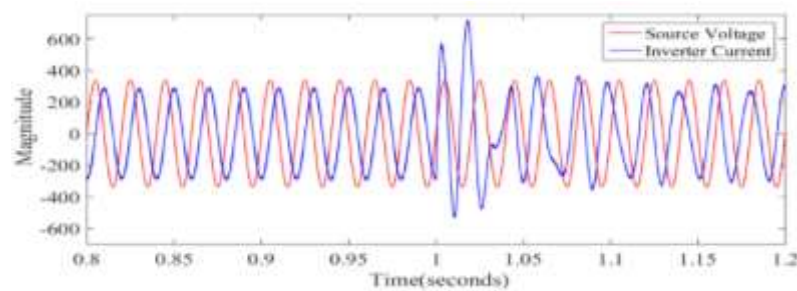
d. Ripple in DC link Voltage

Figure 7. STATCOM response for variation of load from RL to RC at 1 sec with Sinusoidal Phase Shifted Carrier PWM



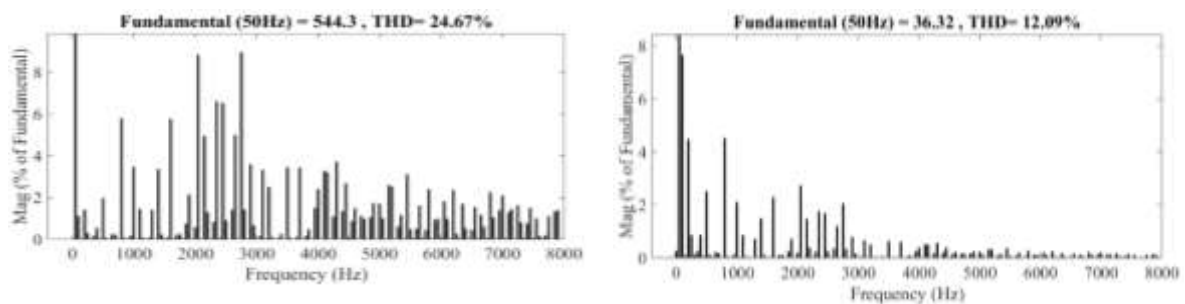
e. Comparison of load and inverter q-components of Currents

Figure 7. STATCOM response for variation of load from RL to RC at 1 sec with Sinusoidal Phase Shifted Carrier PWM



f. Source Voltage and STATCOM current

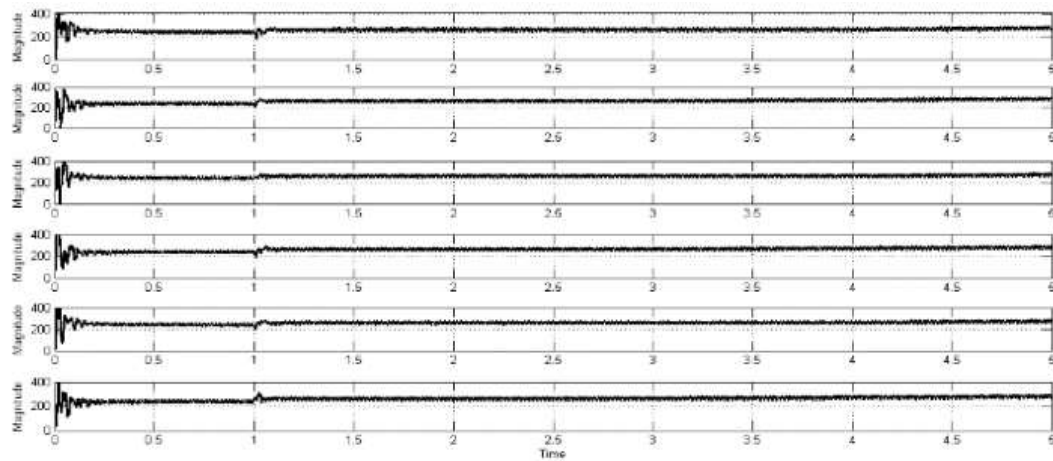
Figure 7. STATCOM response for variation of load from RL to RC at 1 sec with Sinusoidal Phase Shifted Carrier PWM



a. Harmonic analysis of STATCOM output voltage

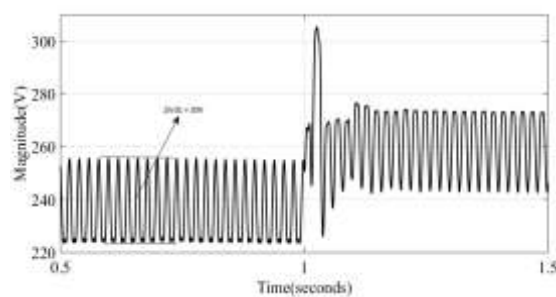
b. Harmonic analysis of STATCOM output current

Figure 8. STATCOM response for variation of load from RL to RC at 1 sec with Sinusoidal Phase Disposition PWM

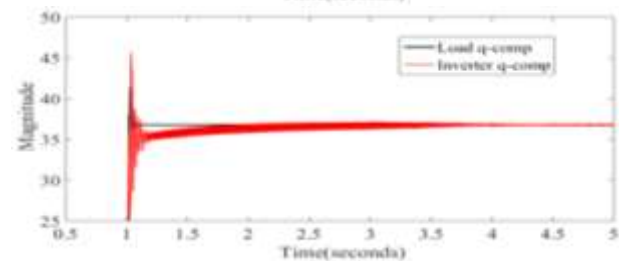
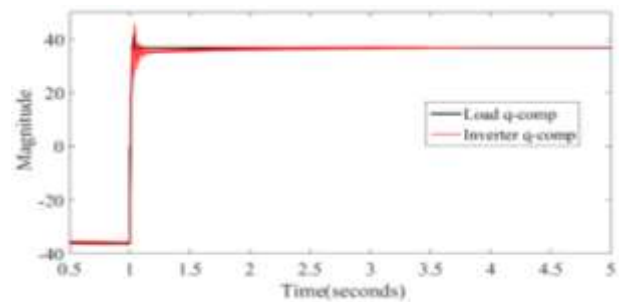


c. DC Link voltages

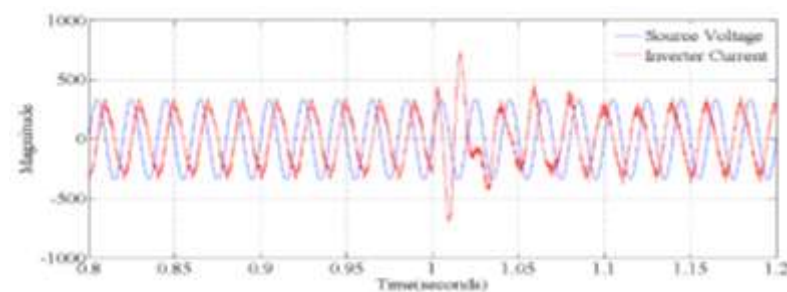
Figure 8. STATCOM response for variation of load from RL to RC at 1 sec with Sinusoidal Phase Disposition PWM



d. Ripple in DC link Voltage



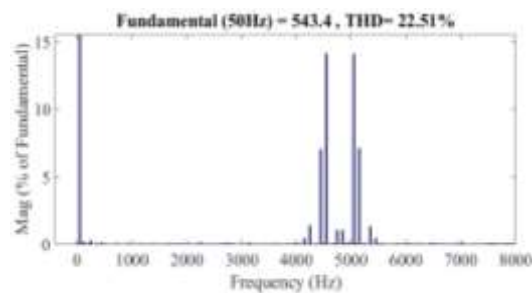
e. Comparison of load and inverter q-components of Currents



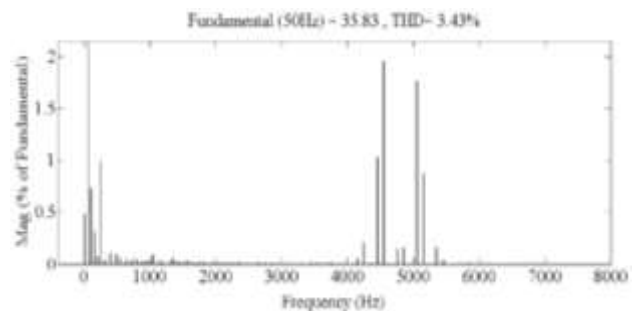
f. Source Voltage and STATCOM current

Figure 8. STATCOM response for variation of load from RL to RC at 1 sec with Sinusoidal Phase Disposition PWM

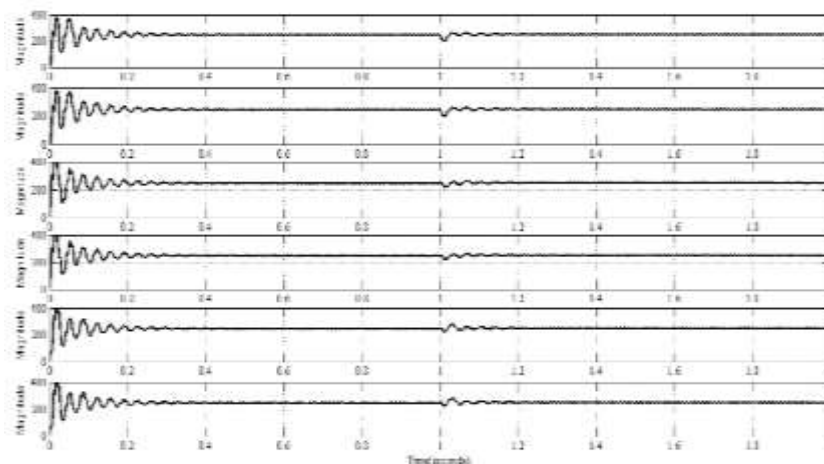
Figure 9 shows the response of STATCOM for various performance parameters such as harmonic analysis of STATCOM output voltage and current, balancing DC-link voltages for all H-bridges, Ripple content in DC-link voltage, comparison of reactive components required by the load and supplied by the STATCOM, and Phasor relations between Source voltage and STATCOM current for the variation of load from RL to RC at 1 sec by using THIPSCPWM technique. It is observed that the STATCOM works perfectly for a reference DC link voltage of 1500 V, this voltage is equally distributed among all the H-bridge DC-link capacitors and it is balanced for all types of load changes. If the load is changed suddenly also STATCOM supplies reactive components required by load. The ripple content in the DC-link voltage is around 10V. The harmonics in the output current is in the order of 3.43 % and in the output voltage is 22.51%. No harmonics observed 4.8 kHz frequency due to PSC technique. After changing the load from inductive to capacitive at 1 sec, the reactive components supplied by the STATCOM changed from negative to positive, but to reach steady state it takes up to 2.5 sec.



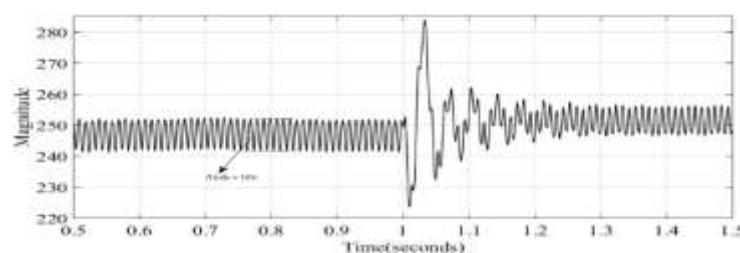
a. Harmonic analysis of STATCOM output voltage



b. Harmonic analysis of STATCOM output current

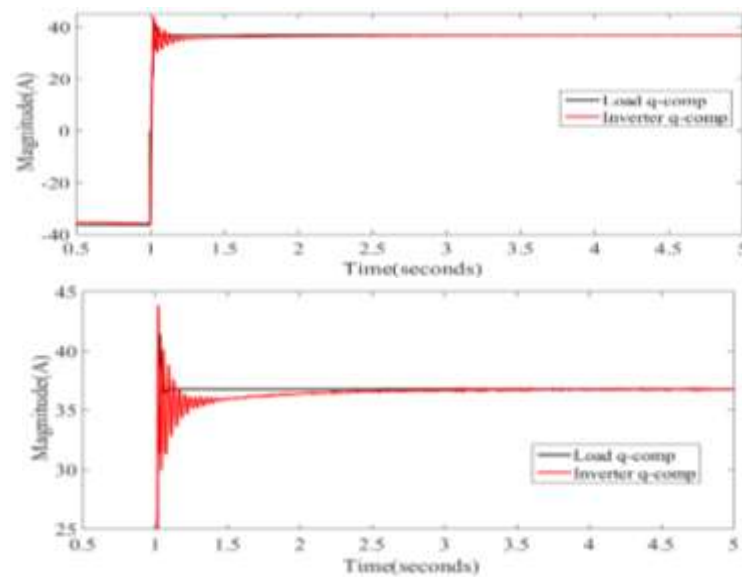


c. DC Link voltages

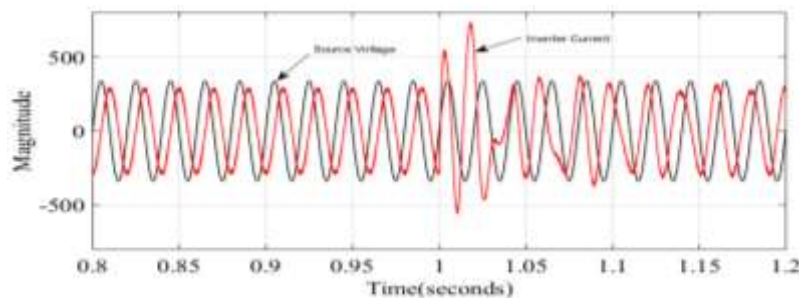


d. Ripple in DC link Voltage

Figure 9. STATCOM response for variation of load from RL to RC at 1 sec with Third Harmonic Injected Phase Shifted Carrier PWM



e. Comparison of load and inverter q-components of Currents



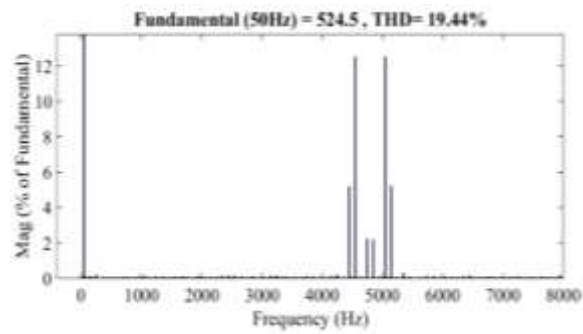
f. Source Voltage and STATCOM current

Figure 9. STATCOM response for variation of load from RL to RC at 1 sec with Third Harmonic Injected Phase Shifted Carrier PWM

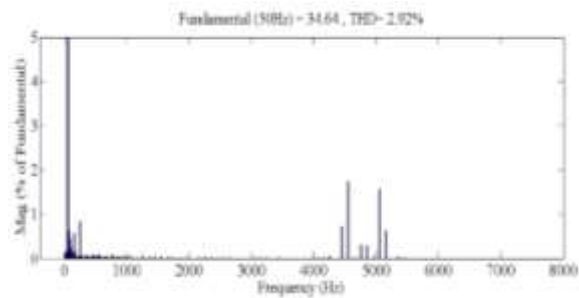
Figures 10 and 11 shows the response of STATCOM for various performance parameters such as harmonic analysis of STATCOM output voltage and current, balancing DC-link voltages for all H-bridges, Ripple content in DC-link voltage, comparison of reactive components required by the load and supplied by the STATCOM, and Phasor relations between Source voltage and STATCOM current for the variation of load from RL to RC at 1 sec with SVPSCPWM and SVPDPWM techniques respectively. It is observed that the STATCOM works perfectly for a reference DC link voltage of 1500 V, this voltage is equally distributed among all the H-bridge DC-link capacitors and it is balanced for all types of load changes. If the load is changed suddenly also STATCOM supplies reactive components required by load.

It is observed from the Figure 10 with the use of SVPSCPWM technique, the ripple content in the DC-link voltage is low it is around 9V. The harmonics in the output current is in the order of 2.92 % and in the output voltage is 19.44%. No harmonics present below 4.8 kHz frequency due to Phase Shifted Carrier technique. After changing the load from inductive to capacitive at 1 sec, the reactive components supplied by the STATCOM changed from negative to positive, but to reach steady state it takes up to 2.5 sec.

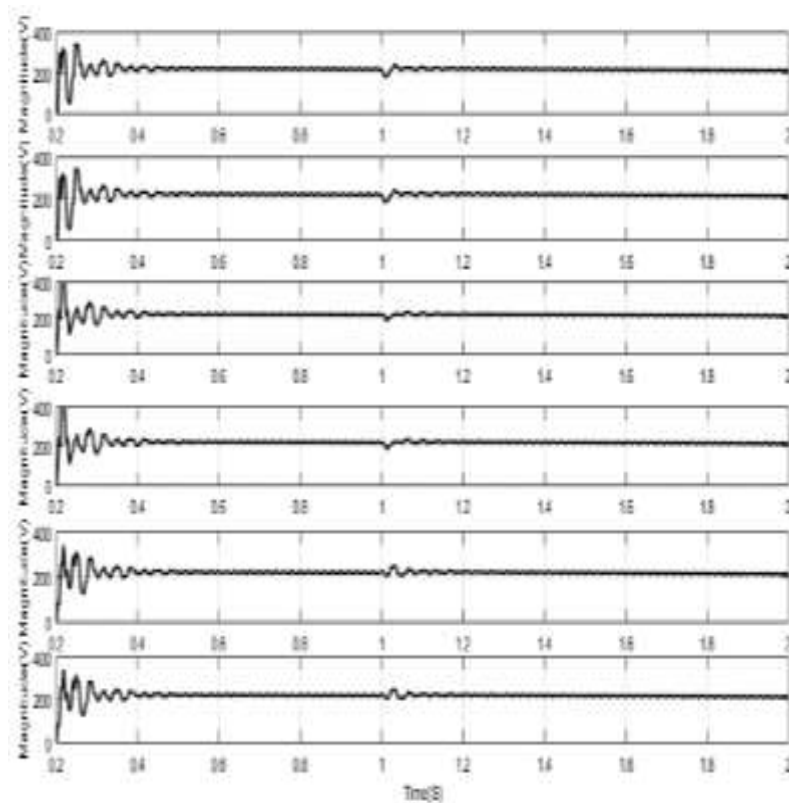
It is observed from the Figure 11 with the use of SVPDPWM technique, the ripple content in the DC-link voltage is high it is around 28V. The harmonics in the output current is in the order of 13.10 % and in the output voltage is 27.22%. After changing the load from inductive to capacitive at 1 sec, the reactive components supplied by the STATCOM changed from negative to positive, but to reach steady state it takes up to 2.5 sec but the ripple content in the STATCOM reactive current component is high. Table III shows the comparison of STATCOM performance with different PWM techniques.



a. Harmonic analysis of STATCOM output voltage

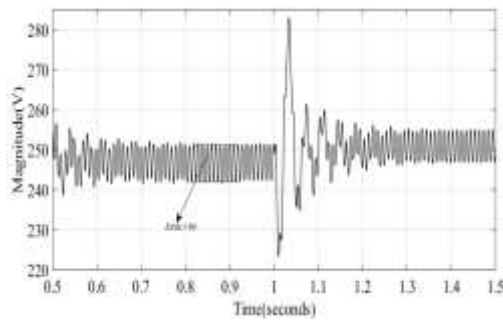


b. Harmonic analysis of STATCOM output current

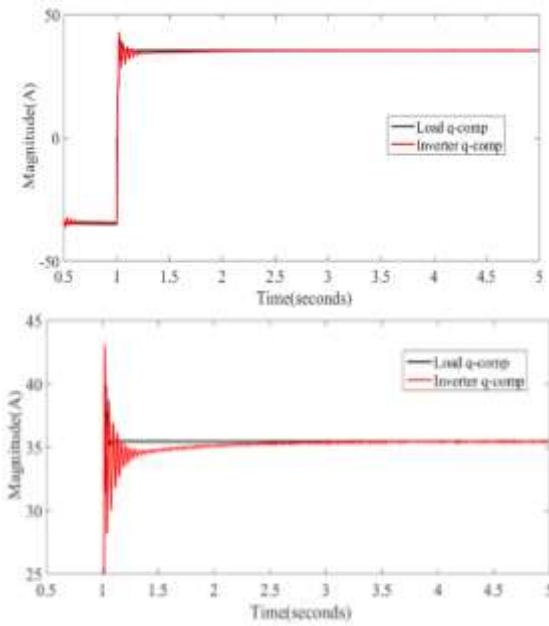


c. DC Link voltages

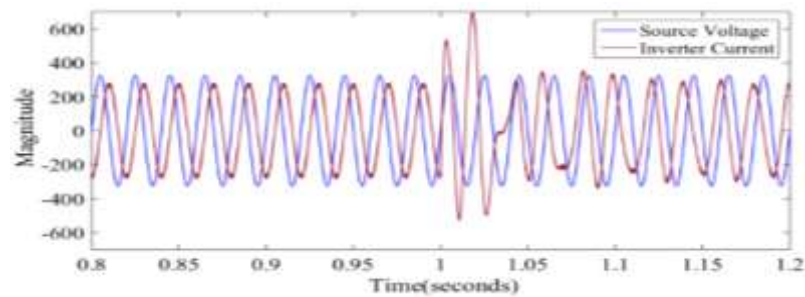
Figure 10. STATCOM response for variation of load from RL to RC at 1 sec with Space Vector Phase Shifted Carrier PWM



d. Ripple in DC link Voltage

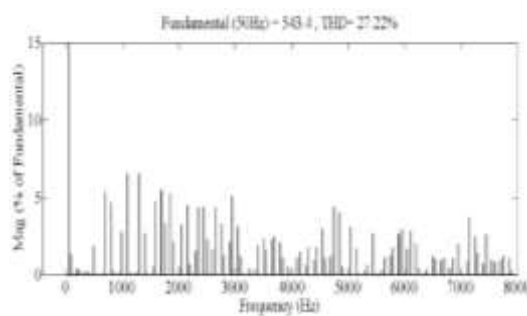


e. Comparison of load and inverter q-components of Currents

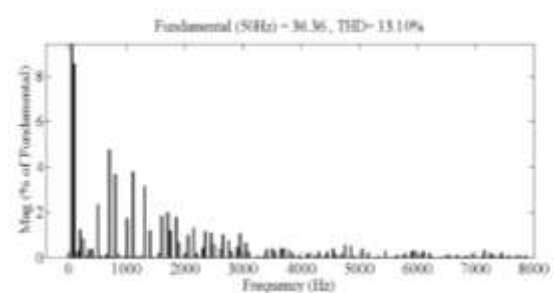


f. Source Voltage and STATCOM current

Figure 10. STATCOM response for variation of load from RL to RC at 1 sec with Space Vector Phase Shifted Carrier PWM

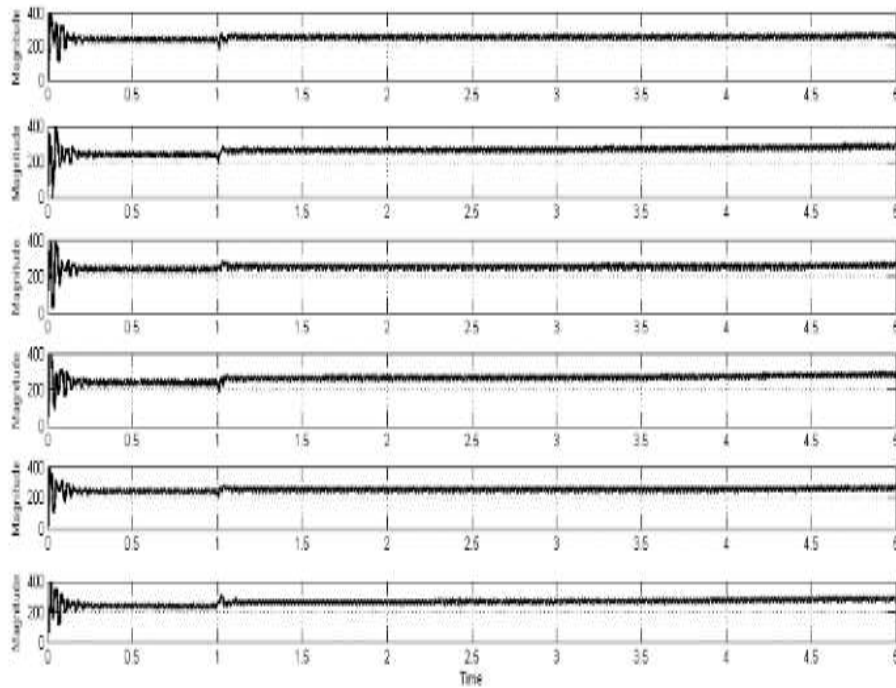


a. Harmonic analysis of STATCOM output voltage

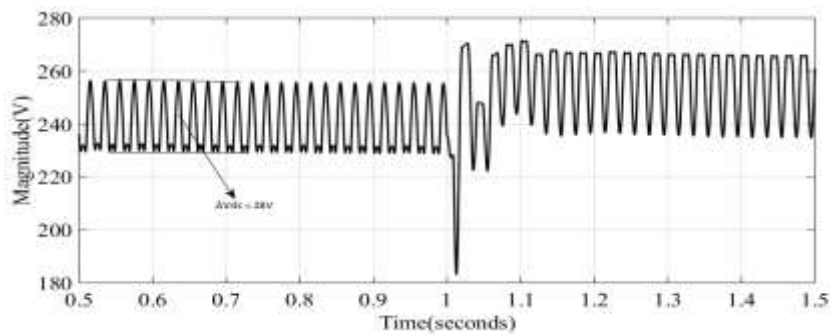


b. Harmonic analysis of STATCOM output current

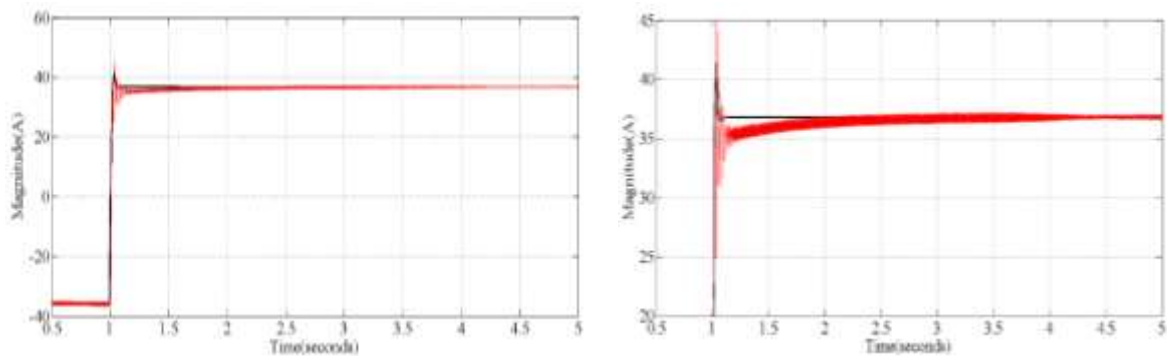
Figure 11. STATCOM response for variation of load from RL to RC at 1 sec with Space Vector Phase Shifted Carrier PWM



c. DC Link voltages

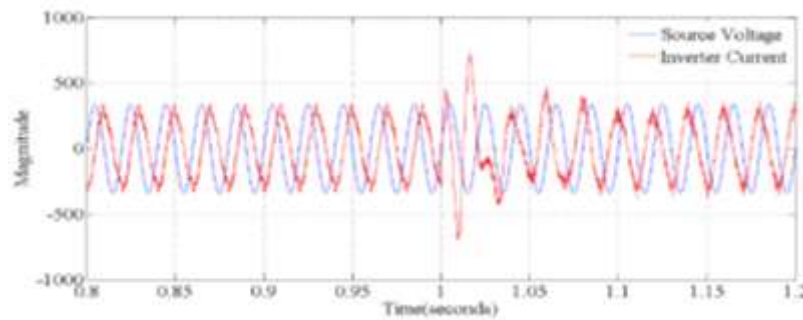


d. Ripple in DC link Voltage



e. Comparison of load and inverter q-components of Currents

Figure 11. STATCOM response for variation of load from RL to RC at 1 sec with Space Vector Phase Shifted Carrier PWM



f. Source Voltage and STATCOM current

Figure 11. STATCOM response for variation of load from RL to RC at 1 sec with Space Vector Phase Shifted Carrier PWM

Table 3. Performance comparison of STATCOM for different PWM Techniques

S. No	Technique	%THD in output voltage	%THD in output Current	Ripple in DC-link voltage (V)	Settling time for Reactive component of current (Seconds)
1	SPSPWM	26.31	3.01	9	3
2	SPDPWM	24.67	12.09	30	3.5
3	THIPSPWM	22.51	3.43	10	2.5
4	SVPSPWM	19.44	2.92	9	2.5
5	SVPDPWM	27.22	13.10	28	2.5

5. CONCLUSIONS

The DC link voltage balancing is one of the major problems in cascaded multilevel STATCOM. In this paper, five control strategies are proposed for cascaded H-bridge five level based STATCOM. With these control strategies, the dc-link voltages of all the H bridges are balanced even if the STATCOM mode is converted from one load to another load. In all the circumstances the reactive components required by the load are supplied by the STATCOM. The SVPSPWM strategy produces better output currents and voltages with 2.92% and 19.44% of harmonics respectively with respect to all other techniques. The settling time for the reactive components of currents supplied by STATCOM during the change of load is also less in SVPSPWM technique. Except %THD in the output voltage the SPSPWM is also gives similar performance with respect to SVPSPWM technique. By comparing all PWM technique performances the SVPSPWM technique gives better performance in terms all performance parameters. The implementation of this technique is also very easy.

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