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Design of STATCOM using CHB and its Comparison with other RPC Devices

A. Thamilmaran*, P. Vijayapriya and M. Kowsalya

School of Electrical Engineering, VIT University, Vellore - 632014, Tamil Nadu, India;
thamilmaran.a@vit.ac.in, pvijayapriya@vit.ac.in, mkowsalya@vit.ac.in

Abstract

Background/Objectives: Due to the immense development in distributed generation, the entire power system network requires flexible control of power flow and increased stability. **Methods/Statistical Analysis**: In order to achieve this as well as to improve the reliability of the network, power electronics switches are incorporated at several locations as the control of these switches are comparatively easy and accurate. Cascaded multilevel inverter based static synchronous compensator is one such device that provides better reactive power compensation, improves voltage profile as well as enhances the power factor of the system. **Findings:** This paper is intended to design and analyze Static Synchronous Compensator (STATCOM) utilizing Cascaded H-Bridge (CHB) multilevel inverter. The designed STATCOM has been used for the Reactive Power Compensation (RPC) and power factor improvement for the single end fed power system network modeled in Simulink. Seven levels CHB multilevel inverter has been designed for STATCOM using Sine Pulse Width Modulation (SPWM). The output of the inverter is then filtered using the pi filter to obtain nearly sinusoidal voltage profile. Single end fed power system network has been modeled in Simulink. STATCOM majorly provides reactive power and improve the power factor of the system without any further loading on it. For confirming the effectiveness of the proposed STATCOM compensation, the system has also been analyzed with shunt compensation by fixed capacitor and Thyristor Switched Capacitor (TSC) individually and the same study has been carried out to compare them. **Applications/Improvements:** It has been found that with the STATCOM implemented, the voltage profile of all the bus has increased nearly to 1 pu and the power factor has improved to 0.97 when compared to the other compensating devices.

Keywords: CHB, Fixed Capacitor, Reactive Power Compensation, STATCOM, TSC

1. Introduction

Power Generation and Transmission is a complex process, requiring the working of many components of the power system in order to maximize the output. The steady state analysis may be carried out by finding out the flow of active and reactive power throughout the network and voltage magnitudes and phase angles at all the nodes of the network. If the power flow study indicates that there are voltage magnitudes away from its maximum or minimum limits at certain points in the network, then appropriate control actions become necessary in order to regulate the voltage magnitude. Similarly, if the study indicates that the power flow in the given transmission line is beyond the power carrying capacity and then control actions must be taken[1,2].

To improve the performance of AC power systems, we need to manage the reactive power in an efficient way and this is known as reactive power compensation. Two types of compensation can be used: series and shunt compensation. In recent years, static VAR compensators like the STATCOM has evolved which quite satisfactorily do the job of absorbing or generating reactive power with a faster time response and are a family member of Flexible AC Transmission Systems (FACTS). Other compensators are Fixed Capacitors (FC), Thyristor Switched Capacitor (TSC), Static Synchronous Series Compensators (SSSC) and Unified Power Flow Controller (UPFC)[3]. So the main task is to choose the appropriate compensator for particular application that will do the intended goal efficiently and also cost effectively.

Author for correspondence

Multilevel Inverter Topologies (MLIs) are increasingly being used in medium and high power applications due to their many advantages such as low power dissipation on power switches, low harmonic contents and low Electromagnetic Interference (EMI) outputs. Survey of different topologies of multilevel inverters has been carried out by several researchers[4,5] while several other researchers design the converter for specific applications[6,7]. Modelling of STATCOM under different loading conditions is also presented[8] while in a new topology of cascaded MLI using reduced number of switches is proposed[9] thereby reducing the cost and area as well as complexity of the system. A three level twelve pulse VSI based STATCOM proposed by Snehasish[10] proved that when this STATCOM is utilized properly in distribution system, then there is a considerable improvement in the voltage profile across different types of loads under three phase fault conditions. Colak[11] presented a review on several multilevel voltage source inverter topologies and their control schemes which helps to arrive at a conclusion of application of them

The aim of this paper is to design a three phase seven level Cascaded H Bridge multilevel inverter with minimum THD and apply this for the STATCOM in order to provide reactive power support to the designed three phase single end fed medium length power system at the load end. Also the STATCOM performance is compared with other shunt compensation devices when connected to the same system under system to prove the effectiveness of the proposed design.

2. Cascaded Multilevel Inverter Design

A relatively new inverter topology, Cascaded H-Bridge Multilevel Inverter (CHB) with separate DC source has been used for static var compensation application. Figure 1 shows a configuration of wye-connected seven-level cascaded inverter. The building block for the cascaded multilevel inverter is a single phase H-bridge unit, which consists of two legs with two active switches in each leg. The DC side of an H-bridge unit is a DC capacitor. Each H-bridge unit provides seven voltage levels, +3Vdc, +2Vdc, + Vdc, 0, –Vdc, –2Vdc, –3Vdc. Output terminals of H-bridge units are connected in series. The output voltage is thus the summation of those H-bridge units. The CHB synthesizes a desired voltage from several DC capacitor voltages. The total number of output voltage levels per phase is defined by m = 2n + l, where n is the number of H-bridge units per phase. This cascaded H-bridge inverter can produce a phase voltage with seven voltage levels.

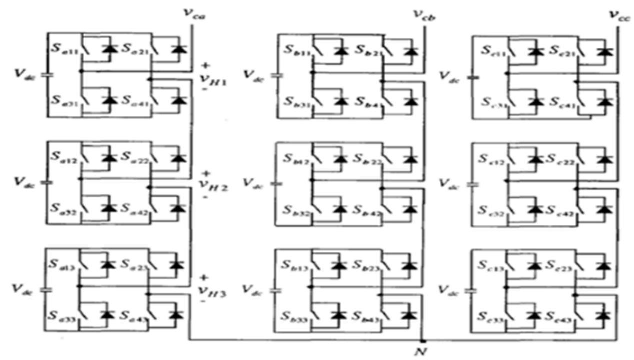


Figure 1. Three phase multilevel inverter.

2.1 Operation of H-Bridge Inverter

The single-phase H-bridge inverter is shown in Figure 2, where v_H and i are H-bridge output voltage and current. Vdc and idc are the capacitor voltage and current.

The switch pair in each leg, (S_1, S_3) or (S_2, S_4), operates in complementary. The combination of possible switching states of the H-bridge is shown in Figure 3[6,10]. The H-bridge output voltage v_H has three possible voltage levels:

- $v_H = V_{dc}$ when S_1 is on and S_2 is off,
- $v_H = -V_{dc}$ when S_1 is off and S_2 is on, and
- $v_H = 0$ when S_1 and S_2 are on or off.

The relationship of switching state combination, switching function and H-bridge output voltage is illustrated in Table 1. In summary, the H-bridge output voltage is given by:

$$v_H = SW.V_{dc} \tag{1}$$

where SW = switching function of H bridge

V_{dc} = input voltage (Volts)

v_H = output voltage of 1 H unit (Volts)

For seven level cascaded H-bridge inverter, the inverter output voltage V_c is the sum of each H-bridge output voltage in one leg, i.e.

$$V_c = V_{H1} + V_{H2} + V_{H3} \tag{2}$$

2.2 PWM Technique in STATCOM

In this paper sinusoidal PWM technique is used to control the fundamental line to-line converter voltage. By comparing the three sinusoidal voltage waveforms with the

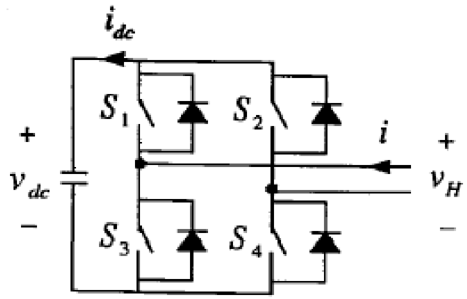


Figure 2. Single phase multilevel inverter.

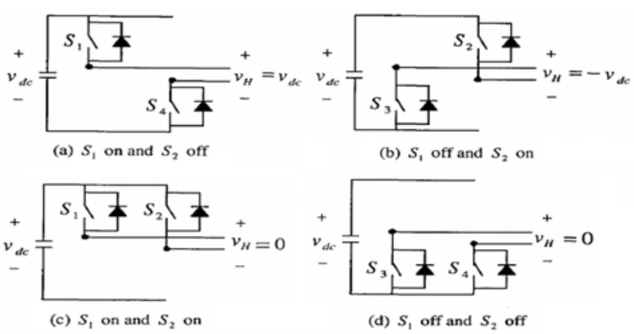


Figure 3. Switching state combinations of H-Bridge inverter.

Table 1. Switch combination, switching function and output voltage of an H-bridge

S_1	S_2	SW	V_H
0	0	0	0
0	1	–1	$-V_{dc}$
1	0	1	V_{dc}
1	1	0	0

triangular voltage waveform, the three phase converter voltages can be obtained. The fundamental frequency of the converter voltage i.e. f_1, modulation frequency, is determined by the frequency of the control voltages, whereas the converter switching frequency is determined by the frequency of the triangular voltage i.e. fs, carrier frequency. Thus, the modulating frequency f_1 is equal to the supply frequency in STATCOM.

The amplitude modulation ratio, m_a is defined as:

$$m_a = V_{control} / V_{tri} \tag{3}$$

Where $V_{control}$ is the peak amplitude of the control voltage waveform and V_{tri} is the peak amplitude of the triangular voltage waveform. The magnitude of triangular voltage is maintained constant and the $V_{control}$ is allowed to vary. The range of SPWM is defined for $0 \le m_a \le 1$ and over modulation is defined for $m_a > 1$. The SPWM carrier signal is given in Figure 4. The reference sinusoidal wave of frequency fr is compared with multilevel carrier triangular waves of frequency fc with different amplitude ranges. Details are mentioned in Table 2. The SPWM outputs for different level carrier waves are as shown in Figure 5.

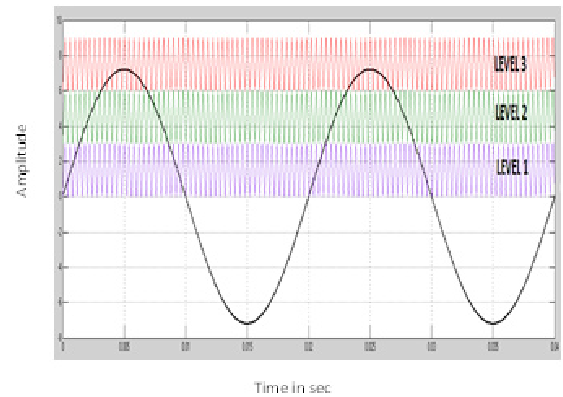


Figure 4. SPWM carrier signal.

Table 2. PWM specifications

Reference Wave		
Frequency (fr)		50 Hz
Modulation Index (m)		0.8
Amplitude		9*m
Carrier Wave		
Frequency (fc)		2500 Hz
Amplitude	Level 1	0–3
	Level 2	3–6
	Level 3	6–9

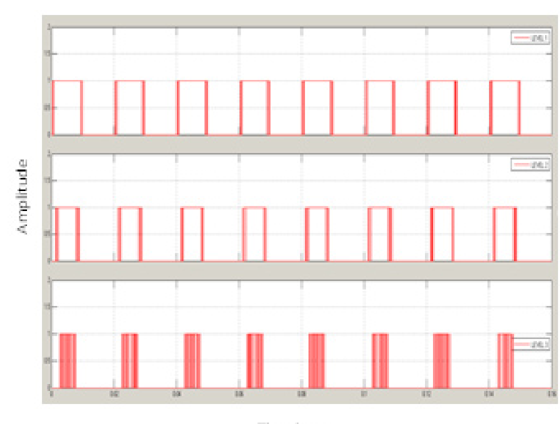


Figure 5. SPWM output.

For conventional multilevel inverter, opposite pairs of switches in H-bridge is triggered with same pulse. This gives the output as shown in Figure 6 which is not as expected. So bypassing is required in Cascaded H-Bridge multilevel inverter. For bypassing, opposite switches are not triggered with same pulse. One switch is triggered with PWM generated as mentioned in previous section and other with normal 50Hz pulse as shown in Figure7.

From the Figure 8, it is clear that the output voltage contains seven levels as required. To meet the IEEE standards for THD, Butterworth Pi LC low pass filter is used to reduce THD within limit.

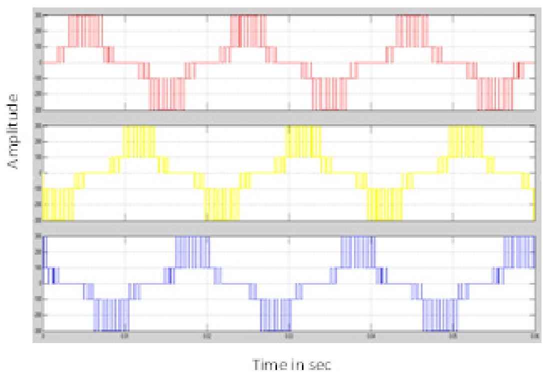


Figure 6. Output phase voltages without bypassing switches.

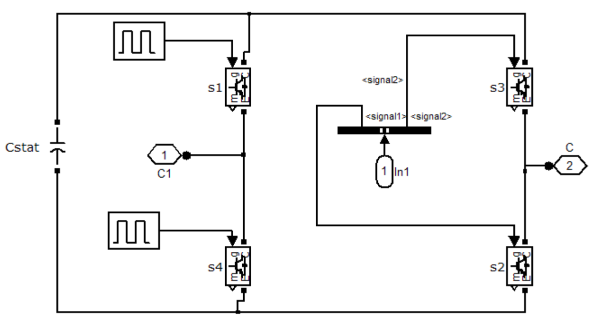


Figure 7. H-Bridge unit with bypass switch.

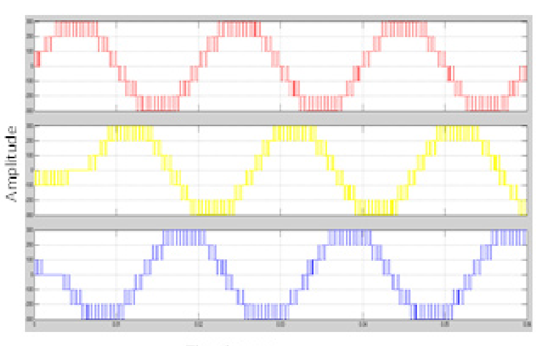


Figure 8 Output phase voltages with bypassing switches.

Filter circuit is shown in Figure 9 and its specifications are given in Table 3. The output voltage of the filter is as shown in Figure10 with the THD of 0.38% which is considerably low.

3. Power System Modeling

In this paper, 130 km medium length transmission line has been selected for study and hence Nominal π method is used for modeling because this method is more accurate than the other two for medium transmission lines. The parameters used in developing the model are given in Table 4. A three phase, 50 Hz power system network has been modeled in Simulink to transfer power efficiently from source to load side as shown in Figure 11. The

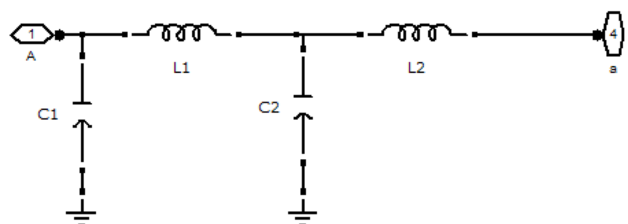


Figure 9. Filter circuit for inverter.

Table 3. Filter specification

Butterworth Pi LC low pass filter	
L1	0.5882mH
L2	0.2436mH
C1	24.36mF
C2	58.82mF

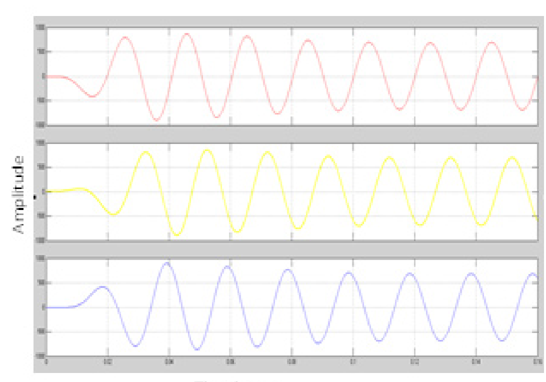


Figure 10. Output of the filter circuit.

Table 4. System specification

Voltage Source		Transformer		
			T1	T2
Connection	star connect	Voltage Ratio	22/220 KV	220/11 kV
RMS Line Voltage	22kV	MVA Rating	50 MVA	40 MVA
MVA Rating	90MVA	Per Unit Winding Resistance (R)	0.2m	0.02m
X/R ratio	7	Per Unit Winding Inductance (L)	0.3m	0.19m
Phase angle of phase A	-40°	Per Unit Magnetizing Resistance (R_m)	500	500
Generator Type	Swing	Per Unit Magnetizing Inductance (L_m)	500	500
Π-Section Transmission Line			**Base Values same as Source**	
Length		130km	kV_b	22kV
Resistance per unit length		0.036Ω/km	MVA_b	90 MVA
Inductance per unit length		0.8mH/km		
Capacitance per unit length		0.0112e-8 F/km		

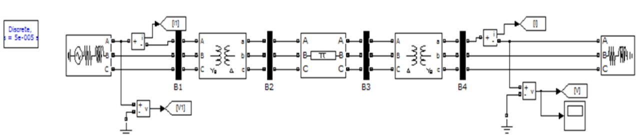


Figure 11. Power system modeling.

system modeled is simulated at no load to analyze its no load performance. The results are mentioned in Table 5.

After analyzing the system at no load, an inductive load of 20 MVA, 11kV 0.6pf lag is connected at the receiving end and system parameters are again monitored. The entire reactive power demanded by the load is supplied by the source only. To improve the system performance, compensating devices are added to meet the reactive power requirements locally thereby increasing the system voltage profile as well as power factor. The various devices chosen here are the FC, TSC for comparison with the performance of developed STATCOM.

3.1 Fixed Capacitor

Fixed capacitors are termed as passive compensators. They modify inductance and capacitance of the line. Apart from switching, they are uncontrolled and incapable of continuous variation. Shunt capacitance may be used to augment capacitance of the line under heavy loading. They generate reactive power which tends to boost the voltage thereby improve voltage regulation. A capacitance of 185 μF is chosen to be connected to the system. After connecting capacitor into the system at 0.08 seconds, power factor of system get improved from 0.6 to 0.8 after sufficient transients as shown in Figure 12(a). System parameters are shown in Table 5.

The following conclusions are drawn from the outputs shown:

- Voltage gets boosted from at receiving end.
- Voltage regulation is improved.
- Reactive power supplied by the source decreases as it is also being fed by the capacitor at the load end.

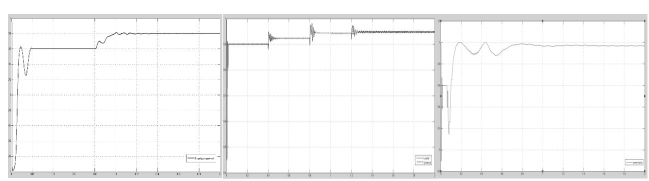
3.2 Thyristor Switched Capacitor

As TSC consists of different capacitors of fixed values, it injects reactive power in a stepwise manner like, 5MVAR, 10MVAR, 15MVAR etc. The number of capacitor banks connected depends upon the reactive power required. More continuous reactive power control is achieved by selecting each capacitor bank following a binary combination. In this paper, each of the capacitor bank is connected at regular intervals of 0.4s. After connecting the TSC into the system, power factor of the system get improved to 0.95 as shown in Figure 12(b). System parameters are shown in Table 5.

The conclusion may be similar with that of connecting fixed capacitor except with the fact that there is still further enhancement in all the required parameters.

3.3 STATCOM

A STATCOM (Static Compensator) designed consists of a seven level Cascaded H-Bridge Voltage Source



(a) FC (b) TSC (c) STATCOM

Figure 12. Power factor improvement with compensators.

Inverter (VSI), a DC energy storage device, a coupling transformer connected in shunt to the distribution network. The VSI converts the DC voltage across the storage device into a set of three-phase AC output voltages. These voltages are in phase and coupled with the AC system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the STATCOM output voltages allows effective control of active and reactive power exchanges between the STATCOM and the AC system. Such configuration allows the device to absorb or generate controllable active and reactive power.

Such device is employed to provide continuous power factor correction using an indirectly controlled converter. STATCOM injects current in quadrature with the bus voltage into the system to compensate reactive power component in load and hence improve power factor of the system. The selection of DC bus voltage and DC bus capacitor is important for proper functioning of STATCOM

The STATCOM is connected in the power system network at 0.06 sec (3/50 sec). The bus voltage varies within 1% of mentioned values and power factor improves to 0.97 as shown in Figure 12(c). System parameters are shown in Table 5.

4. Simulation Results

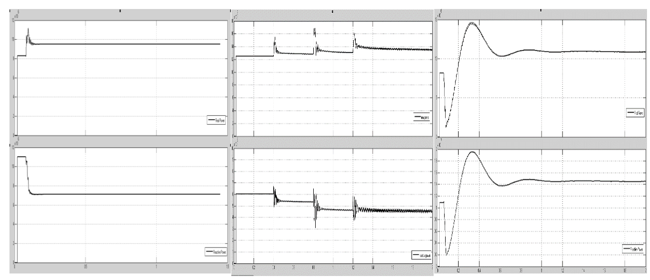
From the Table 5 it is evident that the system performance is enhanced when compensators are connected.

To be in particular, the voltage magnitude and frequency of the system increases considerably. The increment in the values depends on the type of compensators used. Fixed capacitors remains connected to the system and supply the reactive power continuously as shown in Figure 13(a). Hence no control is needed. They neither inject any harmonics nor cause any flow of inrush current. It is cheaper than other two methods by due to lack of control, enhancement in voltage profile and power factor is not predominant.

TSC will be turned on only at the instant when capacitor voltage has same value as that of the system and different capacitors injects reactive power in a stepwise manner as shown in Figure 13(b). Hence there is a possibility that it slightly under compensates or over compensates the system. Also if they are not properly switched, it causes inrush current to flow which may cause a disturbance in the power system.

Table 5. Results

No Load		With Load	With FC	With TSC	With STATCOM
Parameters	Per Unit Values	Per Unit Values	Per Unit Values	Per Unit Values	Per Unit Values
V_b1	1	0.8336	0.8886	0.9445	1.004
V_b2	1	0.8336	0.8886	0.9445	1.02
V_b3	1	0.8232	0.8821	0.9233	1.01
V_b4	1	0.8232	0.8821	0.9233	1.006
P_s	0.002	0.0922	0.1056	0.1464	0.194
Q_s	0.0005	0.1222	0.0789	0.0645	0.0517
P_r	0	0.0902	0.1038	0.1178	0.1207
Q_r	0	0.1204	0.0778	0.0708	0.0609
Power factor	-	0.6	0.8	0.95	0.97



(a) FC (b) TSC (c) STATCOM

Figure 13. Real and reactive power flow with compensators incorporated.

For STATCOM, the bus voltage and voltage of STATCOM should be synchronized properly. It possesses the advantage of being continuously controlled by variation of modulation index of VSI. Hence accurate compensation is possible when compared to the other. The real and reactive power flow is shown in Figure 13(c). However it injects considerable harmonics in the system thus demanding for a separate filter circuit. Also the circuit is much complex and costlier. But when comparing the advantages of improvement in power factor and voltage profile as shown in the Table 5, they are well suited to provide the necessary reactive power compensation at the load side.

5. Conclusion

The seven level Cascaded H-Bridge inverter has been designed in Matlab/Simulink. The VSI has then been implemented to model the STATCOM for reactive power compensation. The output of the STATCOM has been analyzed for harmonic distortion and pi-filter has been implemented to reduce THD within acceptable limits.

Stable and efficient power system network has been modeled in Simulink and its performance is studied both under no load and loading conditions. Nominal-2transmission line model has been preferred over the other two.

The STATCOM model has been connected to the power system network. Phase angle difference between the receiving end voltage and STATCOM output has been kept negligible in order to avoid the real power consumption by the STACOM. The complete model has been studied for the Voltage Profile, Power Factor improvement and Real and Reactive Power on source and load sides. Comparative study among the FC, TSC and STATCOM has also been carried out.

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