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RESEARCH ARTICLE

IMPLEMENTATION OF MULTILEVEL VSC TOPOLOGIES FOR DSTATCOM

***[1]Rakesh, T., [2]Dr. Madhusudhan, V. and [3]Dr. Sushama, M.**

[1]JNTUH, Kukatpally, Hyderabad, India
[2]KORMCE, Kadapa, India
[3]JNTUCEH, Kukatpally, Hyderabad, India

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ABSTRACT

This paper compares three converter topologies for the implementation of custom power flexible ac transmission system (FACTS)controllers, (DSTATCOM): three multilevel topologies (multipoint clamped (MPC) or Diode clamped multilevel converter (DCMLC), chain or flying capacitor (FCMLI), and nested cell or H –Bridge or Cascaded multilevel). In keeping with the need to implement high-power inverters, switching frequency is restricted to line frequency. The study addresses device count, restrictions on voltage control. The proposed medium voltage distribution static compensator (DSTATCOM), with high voltage power semiconductor modules and series& shunt booster transformer, is designed to protect sensitive loads at power distribution systems. A control technique based on voltage and current vectors also proposed for custom power devices. Experimental results carried out by using computer program (MATLAB/Simulink) to validate the performance of the DSTATCOM models. Simulation results show the performance of the proposed medium voltage custom power devices and prove the validity of the proposed topologies. Conclusion drawn from simulation studies and comparison has done for the topologies for applications of custom power devices.

INTRODUCTION

One of the most common power quality problems today is voltage dips. A voltage dip is a short time (10ms to 1 minute) event during which a reduction in R.M.S voltage magnitude occurs. It is often set only by two parameters, depth/ magnitude and duration. The voltage dip magnitude is ranged from 10% to 90% of nominal voltage (which corresponds to 90% to 10% remaining voltage) and with duration from half a cycle to1 min. Ina three-phase system a voltage dip is by nature a three-phase phenomenon, which affects both the phase-to-ground and phase-to-phase voltages. A voltage dip is caused by a fault in the utility system, a fault with in the customer's facility or a large increase of the load current, like starting a motor or transformer energizing. Typical faults are single-phase or multiple-phase short circuits, which leads to high currents. The high current results in a voltage drop over the network impedance. At the fault location the voltage in the faulted phases drops close to zero, where as in the non-faulted phases it remains more or less unchanged (Xiao-Ping Zhang and Jih-Sheng Lai; Fang Zheng Peng, 1996). Voltage dips are one of the most occurring power quality problems. Off course, for an industry an outage is worse, than a voltage dip, but voltage dips occur more often and cause severe problems and economical losses.

***Corresponding author: Rakesh, T.**
JNTUH, Kukatpally, Hyderabad, India.

Utilities often focus on disturbances from end-user equipment as the main power quality problems. This is correct for many disturbances, flicker, harmonics, etc., but voltage dips mainly have their origin in the higher voltage levels. Faults due to lightning, is one of the most common causes to voltage dips on overhead lines. If the economical losses due to voltage dips are significant, mitigation actions can be profitable for the customer and even in some cases for the utility. Since there is no standard solution which will work for every site, each mitigation action must be carefully planned and evaluated. There are different ways to mitigate voltage dips, swell and interruptions in transmission and distribution systems. At present, a wide range of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power applications (Lai and Peng, 1996, Bollen, 2000). Among these, the distribution static compensator (D-STATCOM) for improving PQ. Hingorani was the first to propose FACTS controllers for improving PQ. He termed them as Custom Power Devices (CPD). Due to rapid development of the power electronics industry, a large number of high power semiconductor devices are available for power system applications. An inverter technology for high power and high voltage applications that seems to be gaining interest likely is the multilevel inverter. The main feature of, multilevel inverter is its ability to reduce the voltage stress in each power device due to the utilization of multiple levels on the DC bus. Numerous topologies and modulation strategies have been introduced and studied extensively for utility applications in the recent literature. In the proposed work, the three multi level converter topologies (DCMLI, FCMLI and H-Bridge) will be compared in terms of device count, capacitor size, restrictions on the voltage control, ability to transfer power through the dc link, and ability to maintain the balance of the dc link (in the multilevel configurations). From this, the application areas will be identified where each converter may prove useful. A brief history of power semiconductor devices that are used in custom power devices is presented in Section II. Section III investigates the MVSC topology and three types of MVSC topology that can be used for medium voltage applications are compared. Section IV describes the DSTATCOM model and control strategies with simulink models, In section V gives the simulation results, conclusions are drawn in section VI.

Power Semi Conductor Devices used for Multi level Converters

Recent technology advances in power electronics have been made by improvements in controllable power semiconductor devices. Metal Oxide Semiconductor Field Effect Transistors (MOSFET) and Insulated Gate Bipolar Transistors (IGBTs) have replaced Bipolar Junction Transistors (BJT) almost completely. A remarkable development in MOSFETs took place during the last years. Nowadays MOSFETs are available up to a maximum switch power of about 100kVA.

Conventional GTOs are available with a maximum device voltage of 6 kV in traction and industrial converters. The high on state current density, the high blocking voltages, and the possibilities to integrate an inverse diode are considerable advantages of these devices. However, the requiring of bulky and expensive snubber circuits as well as the complex gate drive are the reasons that GTOs are being replaced by IGCTs. IGCTs are offered only as a press pack device. The symmetrical IGCT is offered by Mitsubishi with a maximum device voltage of 6.5 kV. An increase of the blocking voltage of IGCTs and inverse diodes to 10 kV is technically possible today. Due to the thyristor latching, a GTO structure offers lower conduction losses than an IGBT of the same voltage class. To improve the switching performance of classical GTOs, gate commutated thyristors (GCTs) with a very little turn-off delay (about 1.5μs) have been developed. New asymmetric GCT devices up to 10 kV with peak controllable currents up to 1 kA have been manufactured but only those devices with 6 kV and 6 kA are commercially available. IGBTs were introduced on the market in 1988. IGBTs from 1.7 kV up to 6.5 kV with dc current ratings up to 3 kA are commercially available today. They have been optimized to satisfy the specifications of the high-power motor drives for industrial and traction applications. They are mainly applied in a module package due to the complex and expensive structure of an IGBT press pack. In IGBT modules, multiple IGBT chips are connected in parallel and bonded to ceramic substrates to provide isolation. Both IGCTs and IGBTs have the potential to decrease the cost of systems and to increase the number of economically valuable applications as well as the performance of high-power converters, compared to GTOs, due to a snubber less operation at higher switching frequencies (e.g. 500-1000Hz). The maximum voltage and current ratings for medium voltage power semiconductors are shown in Table 1.

Table. 1 Devices ratings of medium voltage power semiconductors

Power Semiconductors	Manufacturers	Max Voltage Rating	Max Current Rating	Case
GTO	ABB	6 kV	6000 A	Press Pack
	MITSUBISHI	6 kV	3000 A	Press Pack
IGBT	ABB	6 kV	600 A	Module
	MITSUBISHI	6 kV	600 A	Module
	EUPEC	6 kV	600 A	Module
	HITACHI	3.3 kV	1200 A	Module
	TOSHIBA	4.5 kV	2100 A	Module
IGCT	ABB	6 kV	3000 A	Press Pack
	MITSUBISHI	6.5 kV	1500 A	Press Pack

Multi Level Power Converter Topologies

Topological survey

Multilevel voltage source converters have been studied intensively for high-power applications. These converters synthesize higher output voltage levels with a better harmonic spectrum and less insulation stress. However, the reliability and efficiency of the converter are reduced due to an increasing number of Devices. Today there is a large variety of converter topologies for medium voltage application (Watkins and Zhang, 2001and Rodríguez *et al*., 2002). Despite using the same number of switches, there are importance differences between the three implementations of the multilevel inverter in terms of the numbers of passive components and in aspects of their operation.

Table 2. Component requirements for multilevel inverter topologies

TYPE	No. Of Levels	A	B	C	D	E
DCMLC	n- Level	6(n-1)	6(n-2)	n-1	$V_{6n}/(n-1)$	2n-1
	5- Level	24	18	4	$V_{6n}/6$	9
FCMLC	n- Level	6(n-1)	0	3n-1	$V_{6n}/(n-1)$	2n-1
	5- Level	24	0	10	$V_{6n}/6$	9
CHMVSC	n- Level	6(n-1)	0	3n/2 -15	$V_{6n}/(n-1)$	2n-1
	5- Level	24	0	6	$V_{6n}/6$	9

Where
A- Switches- Independent Diodes- Capacitors- Maximum voltage applied- Line to line output voltage levels

Multipoint-Clamped (MPC) Converter

Fig. 1 shows a converter that is known as either the MPC or diode-clamped converter. This converter is essentially an extension of the neutral-point-clamped (NPC) converter which is also known as a three-level converter. The clamp diodes operate across several voltage levels and are normally composed of series connections of diodes (each rated at the same voltage as the main devices). Therefore, the number of clamp diodes for an N_L-level converter is $N_D= (N_L-1). (N_L-2)$. The large number and difficult physical layout of the diodes makes a converter with a large number of levels unattractive.

Chain Converter

This converter is also known as the flying capacitor converter and is shown in Fig. 2. Each cell consists of a pair of switches (one upper and one lower operated as complements) and a capacitor that is not referenced to the dc bus. The capacitors are charged to a multiple of E that is one different from the adjacent cells. The contribution of each cell to the output voltage E is when upper switch is on and zero when the lower switch is on (this view considers the output voltage to be offset by minus half the total bus voltage). If capacitors of the same voltage rating as the switches are used then series connection is required to support the voltages of the outer cells.

H-Bridge or Nested-Cell Converter

The multilevel technique can also be implemented in a series arrangement of standard H-bridge units as shown in Fig. 5. This is known as a chain or a cascade converter. Each H-bridge converter unit provides three voltage levels (-E, 0, E) The total number of N_L levels that can be achieved using this configuration is $N_L = 2N_H+1$, where N_H is the number of H-bridges in series arrangement (There are four switches per

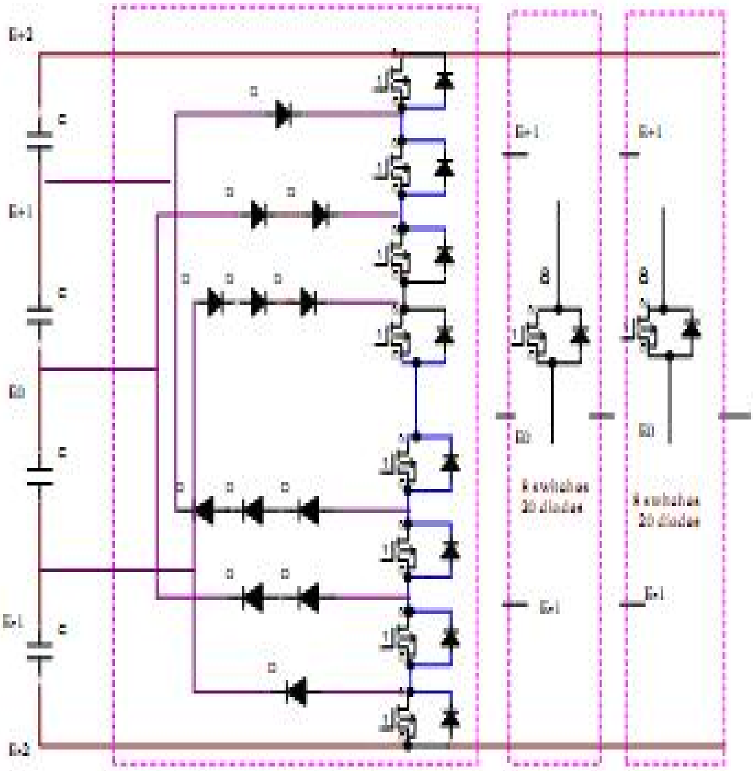


Fig. 1. Schematic diagram of Five-level multipoint -clamped or Diode clamped inverter

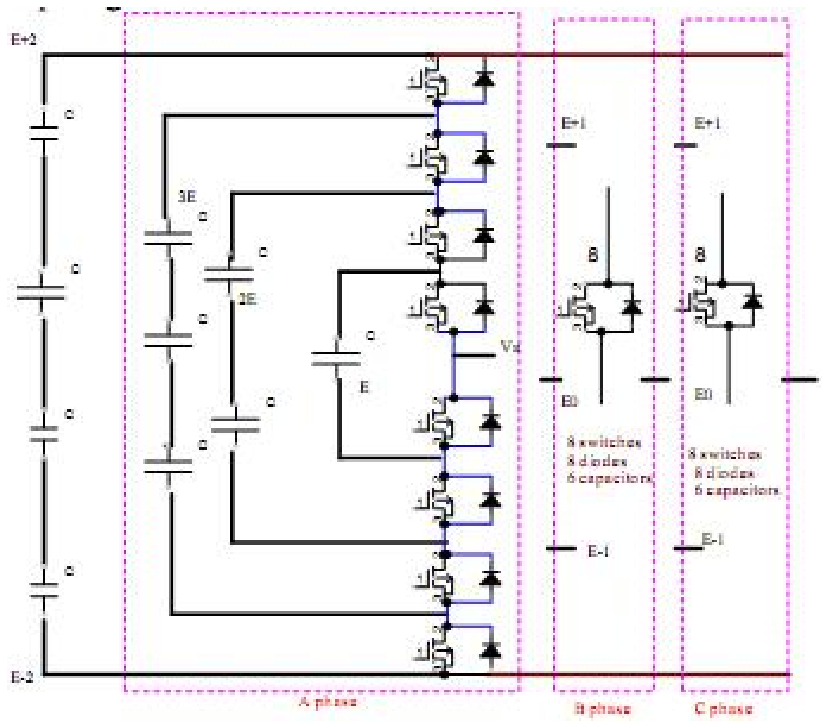


Fig. 2. Diagram for Five-level Chain converter or Flying capacitor multi level inverter

H-bridge. ($N_{S/P}$ = $4N_H$). Table 2 shows the component requirements for various multi level topologies.

Topologies for Medium voltage applications

For medium power industrial applications (e.g. S = 300kVA - 30MVA) the majority of the industrial manufacturers offer different topologies of Voltage Source Converters: Two-Level Voltage Source Converters (2L-VSC), Three-Level Diode-clamped Voltage Source Converters (3L-DC VSC), Four-Level Flying Capacitor Voltage Source Converters (4L-FC VSC) and Series Connected H-Bridge Voltage Source Converters (SCHB VSC). While 4.5kV, 6kV and 6.5kV IGCTs are mainly used in DC VSCs and CSIs respectively; 2.5kV, 3.3kV, 4.5kV and 6.5kV High Voltage IGBTs (HV-IGBTs) are applied in 2L-VSCs, 3L-DC VSCs and 4L-FLC VSCs.

The DC VSC topology has been accepted by several large manufacturers. ABB is using this topology in both their ACS 1000 and ACS 6000 series, in a voltage and power range of 2.3kV-4.16kV and 315kVA-27MVA. DC VSC topology uses high-voltage blocking devices with a relatively low switching frequency capability. This topology has a simple circuit and needs a inductive-capacitive (LC) output filter to operate standard application. The FC VSC is attractive if a very high switching frequency, a low harmonic distortion, and a small output filter or a high output voltage is required. The SCHB VSC topology uses low-voltage blocking devices with a high switching frequency capability. It typically consists of three to six equal H-bridge cells per phase, which results in a seven- to thirteen-level output voltage waveform. An input isolation transformer feeds each of the H-bridges via its own three-phase winding and full-bridge diode in star, delta, zigzag, and combinations are used.

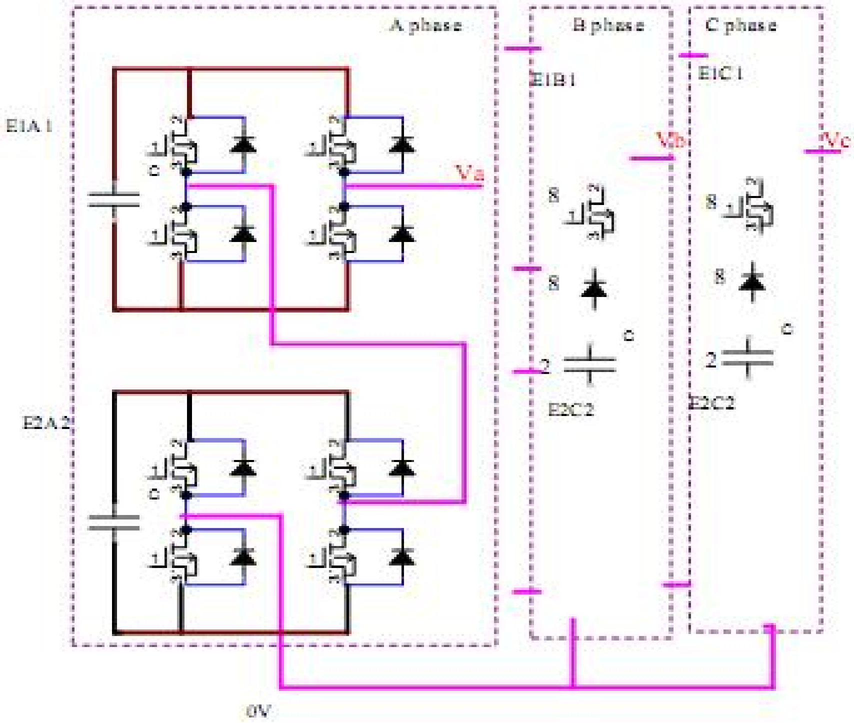


Fig. 3. Five level cascaded multi level converter (H-bridge converter)

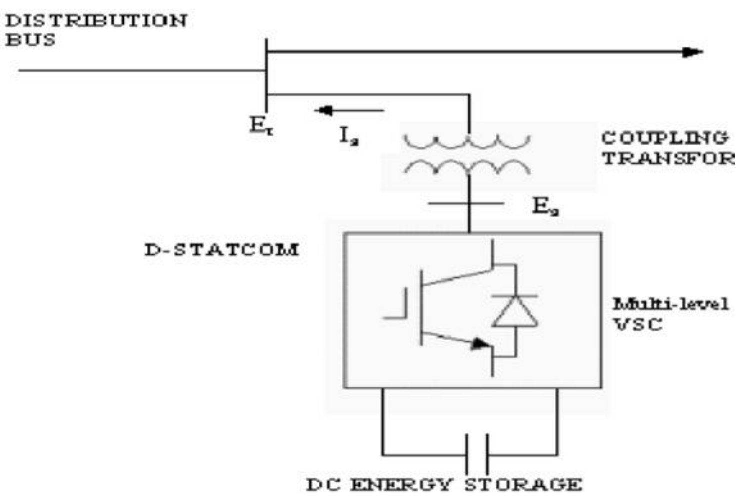


Fig. 4. Schematic diagram for D-STATCOM

This topology has excellent utility grid current and output voltage waveforms. However, the cost of the complex input transformer and the high number of semiconductor devices with their control equipment are its drawbacks. This paper will extend this comparison to the main electric components of the power part, if all converters realize an output voltage THD of 5%according to the standard IEEE519-1999.

The dominant factors in determining which converter topology would be useful in custom power are as follows; independent ac side voltage, size of dc-side capacitor required for balanced and unbalanced current flow, and overall complexity of the converter. As can be seen from the Table II, DC VSC topology uses a low number of capacitors compared to other two topologies. Although this topology requires some additional clamping diodes, its low number of reactive components is usually preferred from the economical point of view. It can be connected to a single dc link voltage. The FC VSC also shares this advantage, but the SCH VSC does not, since this topology requires multiple isolated dc power supplies. Other reason is that FC VSC needs a large dc-side capacitor which may prove difficult and costly. SCH VSC may need booster transformer to reach the desire voltage level. Though, some practical experience with DC VSC reveals technical difficulties that complicate its application, such as: voltage stress and neutral pole balance voltage, the DC VSC has many technical and economical advantages over other topologies. Hence, in this work, The DC VSC is clearly the most attractive topology if a high converter efficiency is required and low switching frequency is applied. At a converter efficiency of 99% and a switching frequency of 1000 Hz the required material costs of semiconductors, gate units, capacitors and inductors are 43% and 173% lower than that FC VSC and SCH VSC respectively. Thus the DC VSC is the most attractive topology for the majority of DSTATCOM application in the power and voltage range. Table III shows the THD values for output voltage and current for various levels of multilevel inverter (Diode clamped MLC).

Table 3. Efficiency, %Thd (Voltage and Current) Comparison Table For Various Levels Of Mlc

S.No.	Level of MLC	Efficiency (%)	THD	
			Voltage	Current
1	2	80.09	97.33	13.45
2	3	83.18	42.28	7.88
3	5	87.24	23.78	3.89
4	7	75.57	16.72	4.12
5	9	54.92	7.67	5.03

Multilevel converter based dstatcom

Shunt voltage controller [Distribution Static Compensator (DSTATCOM)

A D-STATCOM (Distribution Static Compensator), which is schematically depicted in Fig.4, consists of a Voltage Source Converter (VSC), a dc energy storage device, a coupling transformer connected in shunt to the distribution network through a coupling transformer. Fig 5 shows the schematic diagram for multilevel based D-STATCOM and Fig.6 Shows the single line diagram for D-STATCOM.

The modeled STATCOM using VSC topology is being used in the test system to supply reactive power to increase the transmittable power and to make it more compatible with the prevailing load demand. Thus, the shunt connected FACTS device should be able to minimize the line over voltage under light load condition and maintain voltage levels under heavy load condition. Two VSC technologies can be used for the VSC. One of them, VSC is constructed with IGBT/GTO-based SPWM inverters. This type of inverter uses sinusoidal Pulse-Width Modulation (SPWM) technique to synthesize a sinusoidal waveform from a DC voltage source with a typical chopping frequency of a few kilohertz. Harmonic voltages are cancelled by connecting filters at the AC side of the VSC. This type of VSC uses a DC link voltage V_{dc}. Output voltage is varied by changing the modulation index of the SPWM modulator. Thus modulation index has to be varied for controlling the reactive power injection to the transmission line. In another type VSC is constructed with GTO-based square-wave inverters and special interconnection transformers. In this type of VSC, the fundamental component of output voltage is proportional to the voltage V_{dc}. Therefore V_{dc} has to be varied for controlling the reactive power.

The shunt controller is like a current source, which draws from or injects current into the system at the point of connection. The shunt controller may be variable impedance, variable source or a combination of these Variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line. As long as the injected current is in phase quadrature with the line voltage, the shunt controller only supplies or consumes reactive power. When system voltage is low, the DSTATCOM generates reactive power (DSTATCOM capacitive). When system voltage is high, it absorbs reactive power (DSTATCOM inductive). The variation of reactive power is performed by means of a VSC connected on the secondary side of a coupling transformer. The VSC uses forced-commutated power electronic devices (GTOs, IGBTs or IGCTs) to synthesize a voltage V2 from a DC voltage source. Any other phase relationship will involve handling of real power as well. So, the shunt controller is therefore a good way to control the voltage at and around the point of connection through injection of reactive current (leading or lagging) alone or a combination of active and reactive current for a more effective voltage control and damping of voltage dynamics.

The real power (P) and reactive power (Q) are given by

$$P = \frac{E\,.\,V}{X}\sin\delta \qquad (1)$$

$$Q = \frac{E^2}{X} - \frac{E\,.V}{X}\cos\delta \qquad (2)$$

E is the line voltage of transmission line. V is the generated voltage of VSC. X is the equivalent reactance of interconnection transformer and filters and δ is the phase angle of E with respect to V. In steady state operation, the voltage V generated by the VSC is in phase with E (δ=0), so that only reactive power is flowing (P=0). If V is lower than E, Q is flowing from E to V (DSTATCOM is absorbing reactive power). On the reverse, if V is higher than E, Q is flowing from V to E (DSTATCOM is generating reactive power). Since we are using here a VSC based on SPWM inverters hence modulation index is varied for controlling the reactive power injection to the transmission line. A capacitor is connected on the DC side of the VSC acts as a DC voltage source. In steady state the voltage V has to be phase shifted slightly behind E in order to compensate for transformer and VSC losses and to keep the capacitor charged.

So, according to equation-1, the angle is ordered in such a way that the net real power absorbed from the line by this shunt FACTS device is equal to the losses of the converters and the transformer only. The remaining capacity of this shunt converter can be used to exchange reactive power with the line so to provide VAR compensation at the connection point. The reactive power according to equation-2 is electronically provided by the shunt converter and the active power is

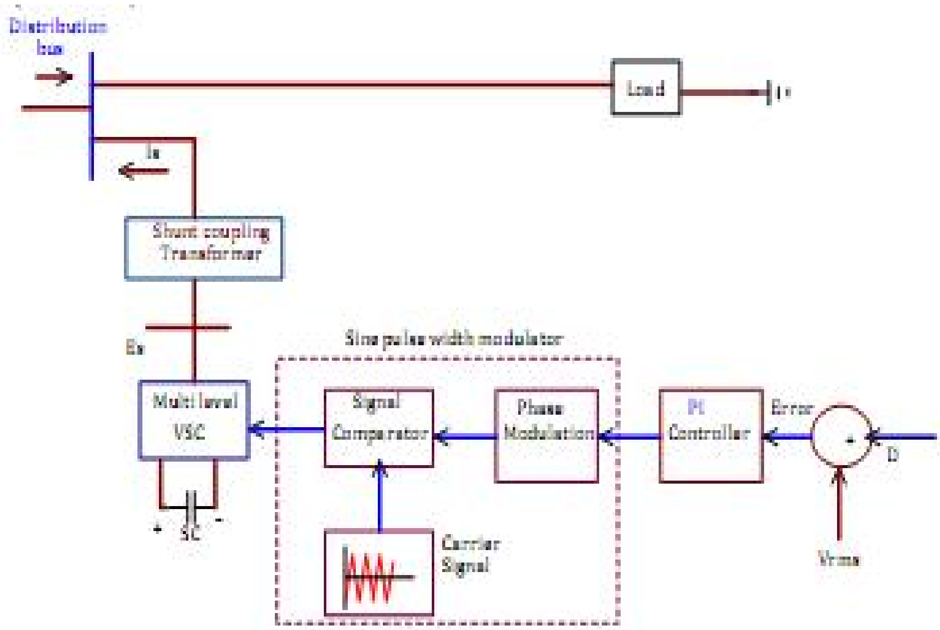


Fig. 5 Basic block diagram for proposed Multilevel based D-STATCOM

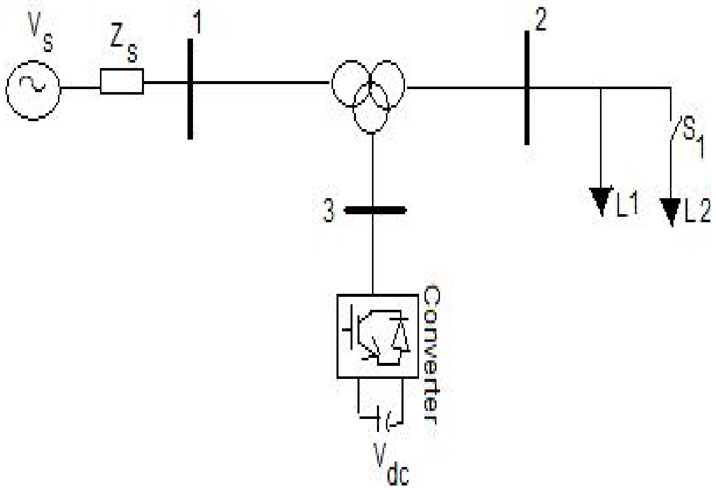


Fig. 6. Simplified single-line diagram of the system with DSTATCOM

Control of D-STATCOM

STATCOM can be controlled in voltage control mode and VAR control mode. The control used in this simulation is AC voltage control mode. The block diagram for the DSTATCOM shown in Fig.4. Mainly, the control is divided into two parts. One is for angle order and another is for the order of modulation index. The shunt converter is operated in such a way as to demand this DC terminal power from the line keeping the voltage across the storage capacitor Vdc constant. transmitted to the DC terminals. The shunt converter reactive current is automatically regulated to maintain the transmission line voltage at the point of connection to a reference value.

The line voltage and Dc link voltage across capacitor are measured to calculate the amount of reactive power to regulate the line voltage and consequently the modulation index is varied in such a way as to calculate reactive power can be injected at the point of connection and thus the shunt FACTS device acts as a voltage regulator. The SPWM firing pulses to the GTOs are obtained by comparing the PWM carrier. The line voltage and Dc link voltage across capacitor are measured to calculate the amount of reactive power to regulate the line voltage and consequently the modulation index is varied in such a way as to calculate reactive power can be injected at the point of connection and thus the shunt FACTS device acts as a voltage regulator. The SPWM firing pulses to the GTOs are obtained by comparing the PWM carrier signal and the reference sine wave. The amplitude of reference sine wave is 1 Volt and frequency is 50 Hz which is similar to system operating frequency. The carrier frequency is set at 1.5 KHz which is 30 times the system operating frequency. The phase lock loop (PLL) plays an important role in synchronizing the switching to the system voltage and lock to the phase at fundamental frequency. The converter is consisted of 12 GTO with additional components. The controller controls the firing pulses from G1 to G12 which are sinusoidal pulse width modulated signals. The following figure shows the block diagram of control strategy to generate only one pulse width modulated signal and 11 signals can be generated similarly. The multi-level VSC converts the DC voltage across the storage device in to a set of three AC output voltages. These voltages are phase couples with AC system through the reactance of the coupling transformer. Suitable adjustment of the active and reactive power exchanges between the D – STATCOM and the AC system. Voltage regulation ,compensation of reactive power, power factor control and voltage flicker control are achieved by controlling multi level VSC connected in shunt with the AC system. The control block diagram of the distribution system with multi-level D-STATCOM is shown in Fig.7

D-STATCOM simulation and results

The main functions of D-STATCOM are reactive power compensation, voltage sag/swell elimination and power factor control. The test system comprises of 230 kV transmission system represented by thevenins equivalent, feeds the primary side of transformer. A varying load is connected to the 11 kV, secondary side of transformer. A five level D-STATCOM is connected through a coupling transformer to the 11kVsecondary winding to provide instantaneous voltage support at the load point. An 800μ F capacitor on the dc side provides the D-STATCOM energy storage capabilities. The reference amplitude for the load voltage is chosen as8.98 kV for each phase that leads to the 11 kV line-line voltage. Fig. 10(a) shows the load bus voltage. The voltage is distorted and unbalanced when DSTATCOM is not connected. Also, there is a 25% voltage dip in phase-b. The DSTATCOM is connected at 0.2 s, and the voltage becomes balanced and sinusoidal. The five-level inverter output VSC at the primary of the transformer is shown in Fig. 10(b).

The voltage is controlled against unbalancing in the source and harmonic distortion due to the nonlinear load. During simulation period 0.3 to 0.5 sec, a step increase in the load of magnitude 165% is applied. In this case the RMS voltage drops by 27% with respect to the reference voltage value of 1.0 pu at 0.5 sec, the heavy load is withdrawn. In this case, the RMS voltage at the load point is very close to the reference voltage value of 1.0 p.u. In the simulation period of 0.9 to 1.2 sec the capacitor banks are connected to the high voltage side of the network.

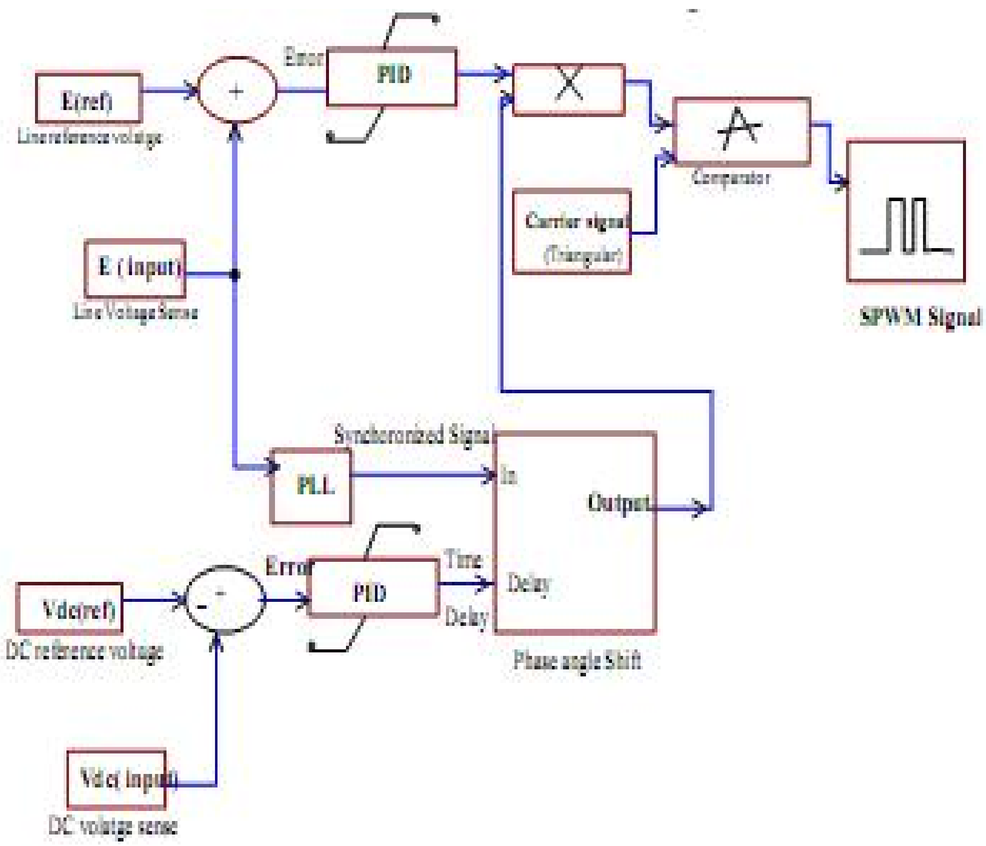
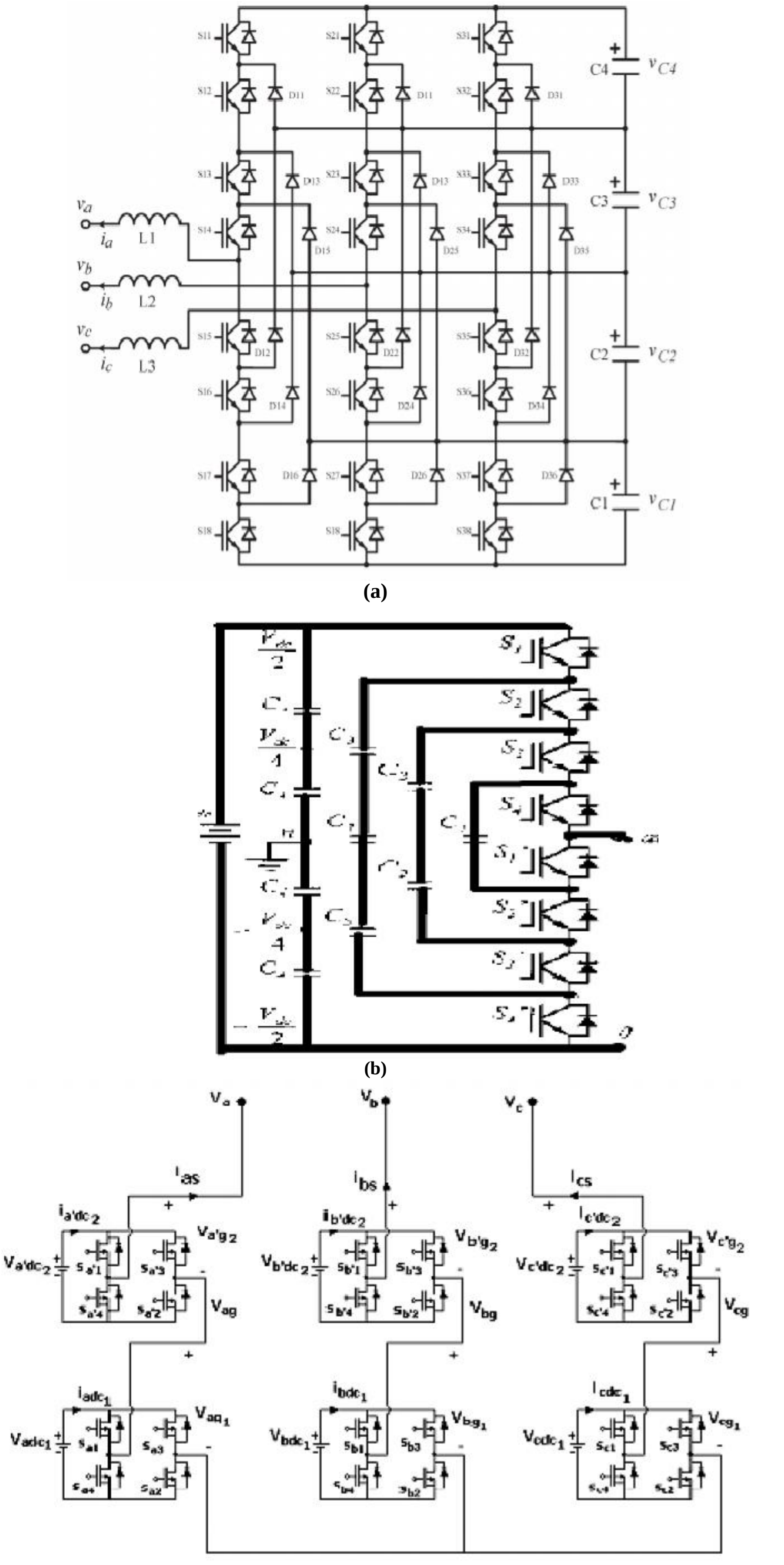


Fig. 7. Control block diagram for D-STATCOM



(a)

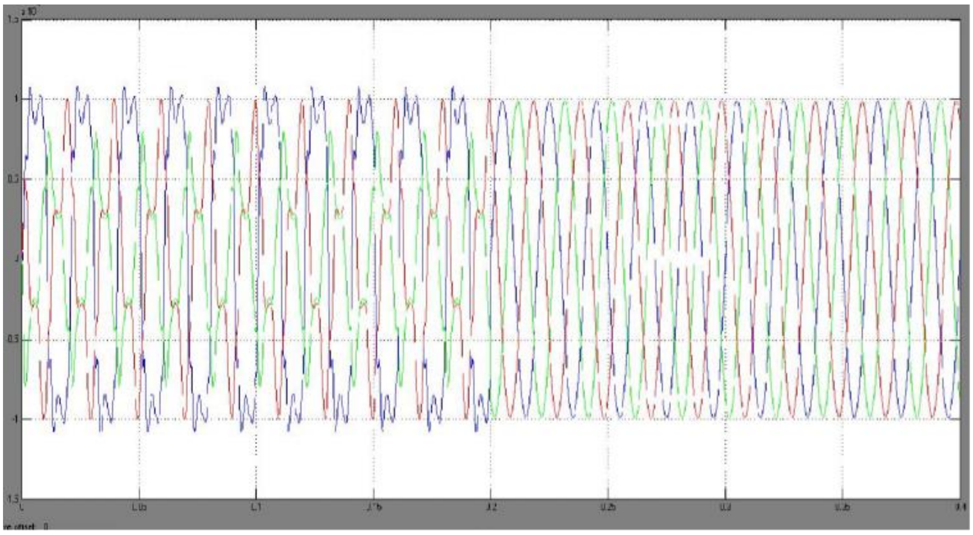
(b)

(c)

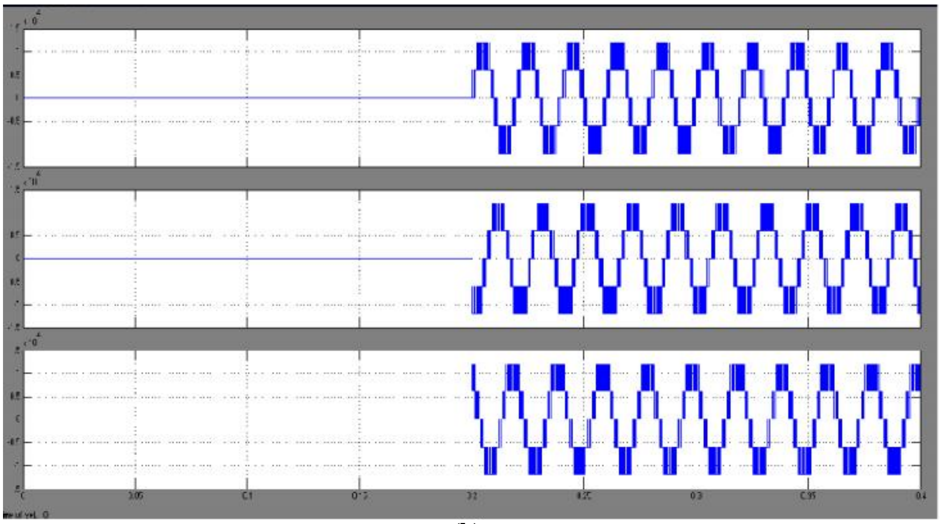
Fig. 9. MATLAB Simulink model of (a) DCMLC, (b) FCMLC (c)H-Bridge VI. SIMULATION RESULTS

Table 4. Control performance comparison of multilevel vsc

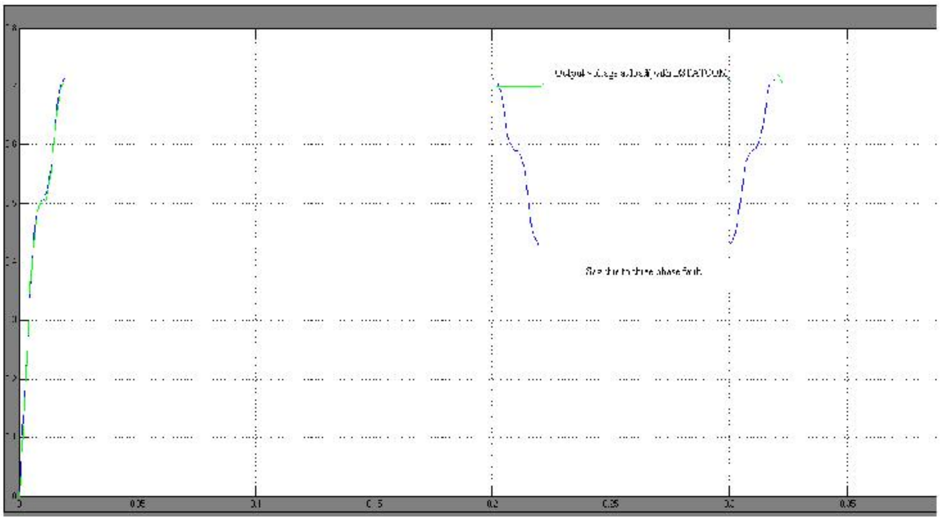
Type of VSC	Response Time (ms)	Compensation (%)	Voltage THD (%) (Output of FACT Controller)	Phase Shift (In Degrees)	Cost(Indian Rupees) for 5 Level
DCVSC	0.5	45	2.23	2-5	2,58,235
FCVSC	1.2	66	3.54	3-7	3,38,793
H-Bridge VSC	0.9	52	1.5	2-6	2,13,967



(a)



(b)



(c)

Fig.10 (a) load voltage when DSTATCOM connected at 0.2 sec. (b) VSC voltage at 0.2 sec. (c) Sag compensation in RMS voltage with D-STATCOM for three phase fault condition

In this case, the RMS voltage increases by 27% with respect to the reference voltage value of 1.0 p.u as shown in Fig.10(c). When voltage sag occurs, the D-STATCOM connected to system supplies reactive power to the system, In spite of sudden load variations, the regulated RMS voltage show a reasonably smooth profile, where the transient overshoot is almost nonexistent. The magnitude of these transients is kept within 6% with respect to the reference voltage. In fact, they do not last for more than two cycles.

Conclusion

As the ratings of various power electronic switches are limited, multilevel VSC topologies are becoming useful for high voltage and high power applications. This will help reducing harmonics penetration as well. Among existing multilevel voltage source converters, three topologies, namely, DC, FC and SCH that can be used for DSTATCOM application are compared. The performance of three multilevel voltage source converters compared with the same (five level) level. The performance com it can be obvious that the power loss of DC VSC had the lowest switching power loss and the amount of switch device is 24 with the same level. The minimum carrier frequency is required for high topology. Table IV shows the performance of multilevel VSC when operated with the sag or swell compensation. The DC VSC has fast response time, high compensation scale, low voltage harmonic distortion, and small over shoot of the voltage with the same condition of the control algorithm. DC VSC is selected for DSTATCOM application as the number of capacitors needed and switching states are less compared to other topologies. The simulation results show the capabilities of proposed custom power devices along with the low pass filer in mitigating voltage sag/swell in a 22 kV distribution system.

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