SIMULATION OF DSTATCOM BASED ON 5-LEVEL CASCADED H-BRIDGE INVERTER

M.Deepika
Department of Electrical and Electronics
Sri Vishnu Engineering College for Women

Mrs.S.M.Padmaja
Department of Electrical and Electronics
Sri Vishnu of Engineering College for women

***Abstract:*: In distribution system (DS), the majority of power consumption has been drawn in reactive loads. These loads are drawn in low power factor and therefore give rise to reactive power burden in the distribution system. So that DSTATCOM controller is used to compensate reactive power, correction of power factor and elimination of current harmonics. This paper presence the 5-Level Cascaded H-bridge Inverter as DSTATCOM for compensation of Balanced and Unbalanced Linear and Non-Linear Loads by using Level Shifted and Phase Shifted PWM techniques. The advantage of CHB Inverter is reducing the number of switches and thus switching losses. The P-Q reference frame theory is used to generate the reference currents for the converter and these reference currents are the reference signals for the PSCPWM and LSCPWM to generate PWM Modulation Waveform while Proportional and Integral Control (PI) is used for DC bus voltage regulation. Finally, the results are compared between the without and with DSTATCOM obtained through MATLAB/Simulink Software.**

Keywords: *Multilevel Inverters-Cascaded H-Bridge Inverter, DSTATCOM, Reactive Power, PWM Techniques- PSCPWM, LSCPWM.*

I.INTRODUCTION

The majority of power consumption has been drawn in reactive loads such as fans, pumps etc. These loads draw lagging power-factor currents and therefore give rise to reactive power burden in the distribution system. Moreover the situation worsens in presence to unbalanced loads. The excessive reactive power demand increases feeder losses and reduces the active power flow capability of distribution system where as unbalancing affects the operation of transformers and generators. Reactive power plays a vital role on the security and stability of power system. Therefore, the reactive power compensation is necessary in the power systems [1]-[4].

In recent years, Flexible Alternating Current Transmission System (FACTS) Technology has a development of Power Electronic devices. As a part of Facts, STATCOM can be treated as a power electronic version of the synchronous condenser [7]. It is called as DSTATCOM because its main application is used in the distribution system. At present these are not applied in High Voltage of High-power Applications, due to the Large Capacity of the Switching Devices and High Voltage Levels. Because of this, Multilevel Technology[5] have been used, it may be easier to produce a high-power , high-voltage inverter with the multilevel structure and it have less switching devices, and low switching frequency for each switching device. The Multilevel Inverters can be classified into three types. Which are Diode-Clamped Multilevel Inverter [6], Flying Capacitor Multilevel Inverter [7] and Cascaded H-Bridge Inverter. Cascaded Multilevel Converter has a low Harmonic Distortions at the output voltage levels, and it has simple control system than other kinds of multilevel inverter. Moreover its H-Bridge modules have a flexible configuration and reliable performance [8]-[10]. Here, Cascaded Multilevel Structure is used as the DSTATCOM.

The control Strategy of DSTATCOM is, when the voltage is kept constant. The Control of reactive current is also control the reactive power. The unbalance of the DC bus voltage is mainly due to the internal loss of the converter. So, we are using method of closed loop feedback P-I Control. It is used to control DC bus Voltage, Overall and Individual control of each cascade module. The Bus voltage improves the control accuracy. By using this control strategy, we can generate reference currents for the converter.

The most popular PWM Techniques for CHB Inverter are Phase Shifted Carrier PWM [11] and Level Shifted Carrier PWM [12]. The first one makes several triangular carriers, which are same in amplitude and frequency, separate a certain angle in phase, and compare them with the modulation wave to generate PWM waveforms. And carrier phase disposition PWM first superposes several triangle carriers of same amplitude, and then compares them with the modulation wave to get the PWM waveform.

In the following sections, section2 discuss about the main circuit topology under this discuss about the A. main circuit, B. Mathematical modeling. Section3 discuss about the control strategy of DSTATCOM. Section 4 discuss about the Modulation Method. Section 5 discuss about the simulation, gives the simulation diagrams and results. Finally, section6 discuss the conclusion and references.

II. MAIN CIRCUIT TOPOLOGY

A. Main Circuit

Fig.1is the circuit diagram of 5-Level CHB-DSTATCOM. Here $U_s$is the Source voltage and $U_c$is the Output voltage and R is the resistance and L is the inductance of the converter. A 5-Level Cascaded H-Bridge inverter is in parallel with the power line through the reactor. By adjusting the phase and magnitude of the AC output voltage of the converter, the converter can sent or absorb reactive power that meets the requirements and achieves the dynamic reactive power compensation. This is the basic principle of CHB-DSTATCOM.

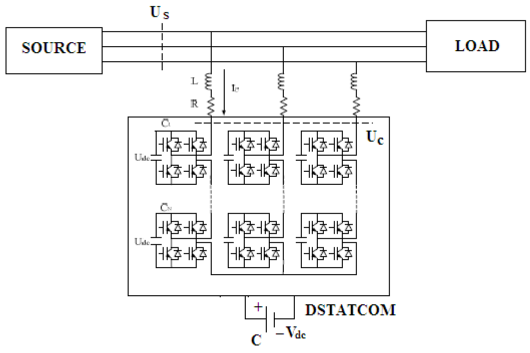


Fig 1. Main Circuit of DSTATCOM

The voltage drop of the connected reactor has generated by the compensation current it can also filter the some of the high harmonics are generated by the source side. If the phase angle difference of 90^0 between each cascaded module, no active power is consumed, and the capacitor voltage does not changes. Actually, if the phase angle difference produces minor changes, the active power flow between the compensator and the power grid and then the Dc bus voltage will produce changes. So, by adjusting the output voltage and currents of the H-Bridge modules, the DC Bus voltage can also be corrected. If the DC Bus voltage is controlled the reactive power can also be controlled.

B. Mathematical Model:

The single phase equivalent circuit diagram of 5-level CHB-DSTATCOM as shown in the figure.

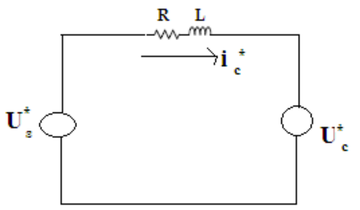


Fig 2 Single Phase equivalent circuit

Assuming the three-phase voltage equations can be expressed as,

$$u_{sa}=\sqrt{2}U_s\sin(\omega t)$$
$$u_{sb}=\sqrt{2}U_s\sin(\omega t-\tfrac{\sqrt{2}}{3})$$
$$u_{sc}=\sqrt{2}U_s\sin(\omega t-\tfrac{\sqrt{2}}{3}) \qquad (1)$$

From the single-phase equivalent circuit, the relationship of three-phase voltage and currents as follows,

$$L\frac{d}{dt}\begin{bmatrix}i_a\\ i_b\\ i_c\end{bmatrix}+R\begin{bmatrix}i_a\\ i_b\\ i_c\end{bmatrix}=\begin{bmatrix}u_{sa}\\ u_{sb}\\ u_{sc}\end{bmatrix}-\begin{bmatrix}u_{ca}\\ u_{cb}\\ u_{cc}\end{bmatrix} \qquad (2)$$

Changing eq (2) from the three-phase to two-phase coordinate system,

$$L\frac{d}{dt}\begin{bmatrix}i_d\\ i_q\end{bmatrix}+R\begin{bmatrix}i_d\\ i_q\end{bmatrix}-\omega L=\begin{bmatrix}u_{sd}\\ u_{sq}\end{bmatrix}-\begin{bmatrix}u_{cd}\\ u_{cq}\end{bmatrix} \qquad (3)$$

In (3), the transformation matrix C_{dq} is,

$$C_{dq}=\frac{2}{3}\begin{bmatrix}\sin(\omega t) & \sin\left(\omega t-\frac{2\pi}{3}\right) & \sin(\omega t+\frac{2\pi}{3})\\ \cos(\omega t) & \cos\left(\omega t-\frac{2\pi}{3}\right) & \cos(\omega t+\frac{2\pi}{3})\end{bmatrix} \qquad (4)$$

Equivalent block diagram of the system can be obtained from the equations above by applying Laplace transform.

III. CONTROL STRATEGY OF DSTATCOM

Control Circuit will generate reference signal for converter by using P-Q Theory.

A. Reactive Current Control

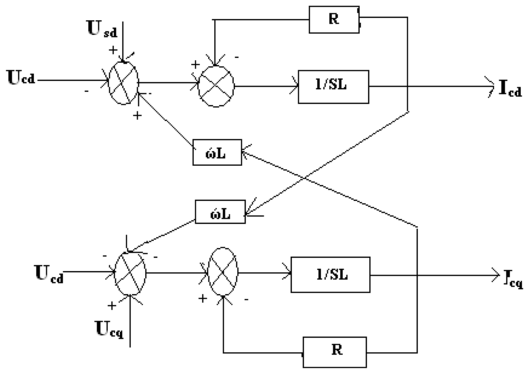


Fig 3 Equivalent diagram of DSTATCOM

Fig 3 is the Equivalent diagram of DSTATCOM. The active current $\boldsymbol{i_{cd}}$ and reactive current $\boldsymbol{i_{cq}}$ couple each other because of the existence of connected reactor, so if one change, the other will change too, which is not conductive to reactive power control. The states feedback decoupled reactive power control method is used to introduce two intermediate control variables is $\boldsymbol{x_1}$ and $\boldsymbol{x_2}$, which will control the active current $\boldsymbol{i_{cd}}$ and reactive current $\boldsymbol{i_{cq}}$ respectively.

$$L\frac{d}{dt}\begin{bmatrix}i_{cd}\\ i_{cq}\end{bmatrix}+R\begin{bmatrix}i_{cd}\\ i_{cq}\end{bmatrix}=\begin{bmatrix}x_1\\ x_2\end{bmatrix} \qquad (5)$$

In (5), the transformation matrix is:

$$\begin{bmatrix}x_1\\ x_2\end{bmatrix}=K_p\begin{bmatrix}i^*{}_{cd}-i_{cd}\\ i^*{}_{cq}-i_{cq}\end{bmatrix}+K_I\begin{bmatrix}\int(i^*{}_{cd}-i_{cd})dt\\ \int(i^*{}_{cq}-i_{cq})\,dt\end{bmatrix}$$

In the equation $\boldsymbol{i^*{}_{cd}}$ ***and*** $\boldsymbol{i^*{}_{cq}}$ are reference values of active current and reactive current.

It can be seen from (5) that there is no coupling between the active current $\boldsymbol{i_{cd}}$ and reactive current $\boldsymbol{i_{cq}}$ and then a real decoupling is achieved. So, if the Bus voltages are controlled then the reactive power can also be controlled. This DC Bus Voltage control can be shown in the firgure3.

B.DC Bus Voltage Control:

(i) Overall Control of Cascaded H-Bridge Modules:

If the DC bus voltage of cascade H-Bridge multi-level converter is influenced by many factors. The unbalance of the DC bus voltage is mainly due to the different switch pulse delay, internal loss of converter and so on.

Here hierarchical control method is used to achieve the Dc bus voltage balance, and it includes the DC bus voltage overall control and individual control of each cascade module. The method of closed-loop P-I control is shown in figure4 to achieve the overall balance voltage.

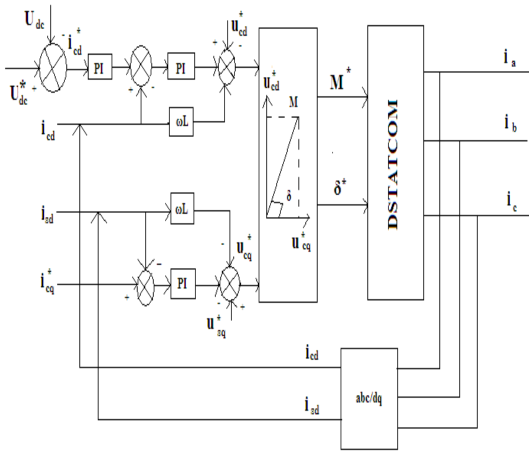


Fig 4 States Feedback decoupled control strategy

If there is a phase angle difference of 90^0 between the each cascaded module, no active power will consumed, and capacitor DC Bus voltage does not changes. Actually, if there is a phase angle difference produces minor changes, so the active power flows between the converter and the Power grid, then the DC Bus voltage changes. So, by the suitable adjustments of output voltage and currents, the Bus Voltage can also be corrected. Therefore the Reactive Power can also be controlled then the supply of the Power Factor is Unity.

(ii) Individual Control of each Cascaded Module:

Figure 5 is the individual control of Cascaded Module. The DC Bus Voltage of this module is U_{dc-ai} and U_{dc} is the Average Value of the Bus Voltage. We can get the Reference value on the basis of error between the P-I Controller. And the Individual Control of the each Cascaded Module is the Compensation Voltage U^*_{ai}. And the $\cos(\omega t)$ is the angle between the 90^0 and the U^*_{ai}.

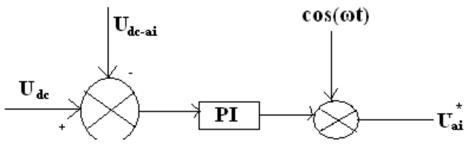


Fig 5 Individual control of each cascade module

The reference voltage of individual module can be expressed as in eq 6 as follows.

$$U^*_{ai} = \left[K_P(U_{dc} - U_{dc-ai} + K_{ai}\int(U_{dc} - U_{dc-ai})\right]\cos(\omega t) \quad --- \quad (6)$$

C.P-Q Theory

By using P-Q Theory, we can generate the refference singal for the converter.

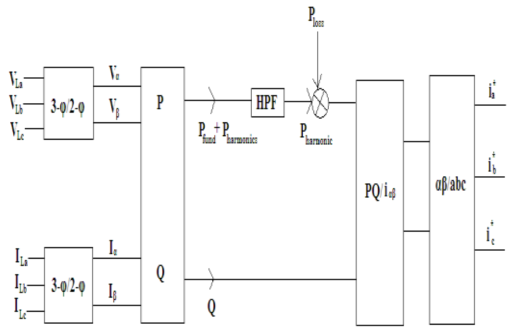


Fig 6 control Strategy of P-Q Theory

Fig 6 is the Control Strategy of P-Q Theory. First we will sense the load voltage and load currents. Then we will convert three phase to two phase to get decouple advantage. So we will get $V_\alpha V_\beta$ and $i_\alpha i_\beta$. From this we will calculate P and Q.

$$P = V_\alpha I_\alpha + V_\beta I_\beta$$

$$Q = V_\beta I_\alpha - I_\beta V_\alpha$$

Change 3-φ voltages to 2-φ voltages. If the 3-φ voltages have a mutual effect is exist, in this case the voltages are dependent. Whereas, 2-φ voltages have a no mutual effect is present, in this case the voltages are independent.

Let us consider 2-φ voltage equations,

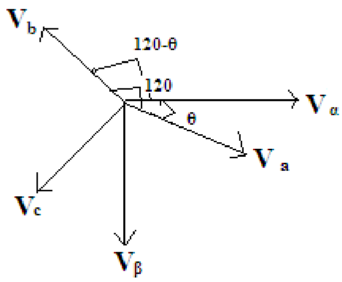


Fig 7, 3-phase to 2-phase vector diagram

$$V_\alpha = V_a\cos(\theta) + V_b\cos(120-\theta) + V_c\cos(240-\theta)$$

$$V_\beta = V_a\cos(\theta) + V_\beta\cos(120-\theta) + V_c\cos(240-\theta)$$

If $\theta = 0$

The transformation matrix of $C_{\alpha\beta}$ is

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 0 & \frac{1}{2} & \frac{\sqrt{3}}{2} \\ 0 & \frac{1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

P consists of two parts $P_{fund} + P_{harmonic}$. So use high pass filter. So we need to compensate only $P_{harmonic}$. Total 'Q' we need to compensate from DSTATCOM, so that supply of Power Factor is Unity. Finally, we will convert PQ to $i\alpha\beta$ and $i\alpha\beta$ to $ia^* ib^* ic^*$. These are called reference currents for STATCOM. Finally we will compensate reference currents and actual current of STATCOM. It will generate references sine wave for Phase Shifted Carrier PWM and Level Shifted PWM.

IV MODULATION METHOD

The most popular PWM Techniques for CHB Inverter are Phase Shifted Carrier PWM and Level Shifted Carrier PWM.

A. Phase Shifted Carrier PWM (PSCPWM)

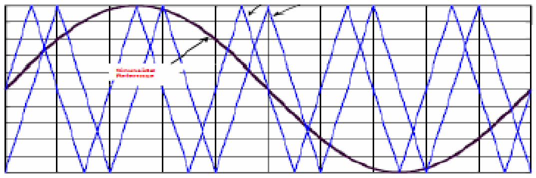


Fig 8 Phase Shifted Carrier PWM

Figure 8 is the Phase shifted carrier pulse width modulation. In general, a multilevel inverter with m voltage levels requires $(m - 1)$ triangular carriers. In the phase shifted multicarrier modulation, all the triangular carriers have the same frequency and the same peak-to-peak amplitude, but there is a phase shift between any two adjacent carrier waves, given by $\phi_{cr} = \frac{360^0}{(m-1)}$. The modulating signal is usually a three-phase sinusoidal wave with adjustable amplitude and frequency, here the Phase Shift of every triangular Carrier is90^0.

B. Level Shifted Carrier PWM (LSCPWM)

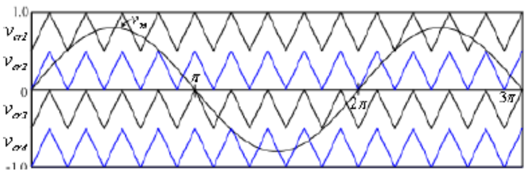


Fig 9 Level Shifted Carrier PWM

Figure-9 is the Level shifted carrier pulse width modulation. An m-level Cascaded H-bridge inverter using level shifted modulation requires (m–1) triangular carriers, all having the same frequency and amplitude. In the Level Shifted carrier modulation, all the triangular carriers have the same frequency and the same peak-to-peak amplitude. The modulating signal is usually a three-phase sinusoidal wave with adjustable amplitude and frequency. And finally, we can get the Level Shifted Carrier waves at the Levels.

(A). COMPARISION OF PHASE SHIFTED AND LEVEL SHIFTED PWM

Table 1 is the Comparison between the Phase Shifted and Level Shifted PWM. Compare to Phase Shifted and Level Shifted PWM, if the Level Shift PWM has the better harmonic content than the Phase Shifted PWM.

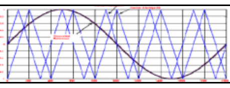
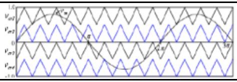
Phase Shifted Carrier PWM	Level Shifted Carrier PWM
	
Switches On-Off is Uniform	Switches On-Off is Non-Uniform
Harmonic Content is poor	Harmonic Content is better

Table .1 Comparison of Phase Shifted and Level Shifted PWM

V. SIMULATION

In order to verify the correctness and effectiveness of the control strategy and modulation method, and also compensate the Reactive Power, Harmonics and Unbalanced Currents using DSTATCOM. The simulation software MATLAB/Simulink is used. The simulation parameters are shown below.

Simulation Parameters	Values
Power grid Voltage(KV)	11
Capacity of devices(MVA)	1
Connected reactance	42
DC Capacitance	4.5

Table2. Simulation Parameters

(A)Simulation Diagram of Without and With a 5-Level CHB-DSTATCOM for Balanced Linear Load

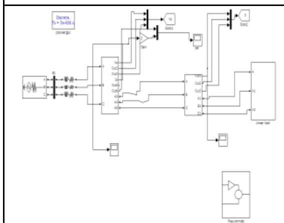
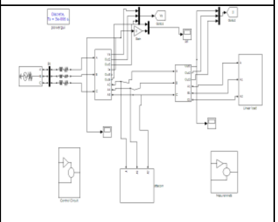
Without DSTATCOM	With DSTATCOM
	

Fig. 10 MATLAB/Simulink diagram of with Balanced Linear Load

(B) Simulation Diagram of Without and With a 5-Level CHB-DSTATCOM for Unbalanced Linear Load

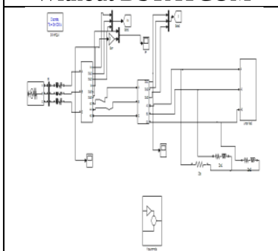
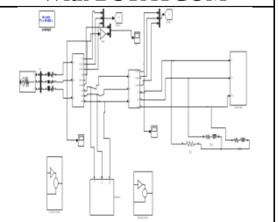
Without DSTATCOM	With DSTATCOM
	

Fig 11 MATLAB/Simulink diagram of unbalanced Linear Load

(C) Simulation Diagram of Without and With a 5-Level CHB-DSTATCOM for Balanced Non-Linear Load

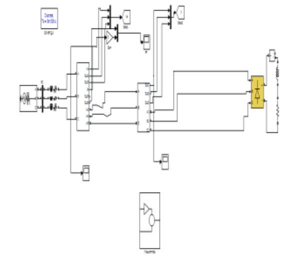
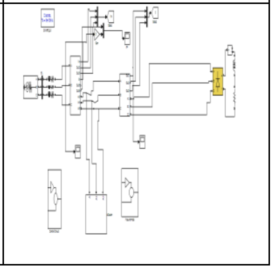
Without DSTATCOM	With DSTATCOM
	

Fig 12 MATLAB/Simulink diagram of Balanced Non-Linear Load

(D) Simulation Diagram of Without and With a 5-Level CHB-DSTATCOM for Unbalanced Non-Linear Load

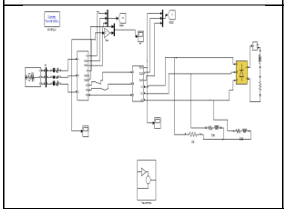
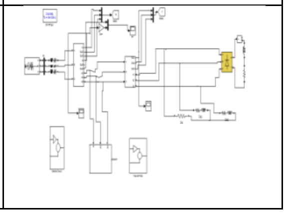
Without DSTATCOM	With DSTATCOM
	

Fig 13 MATLAB/Simulink diagram of Unbalanced Non-Linear Load

(E) Simulation Diagram Of 5-Level CHB-DSTATCOM

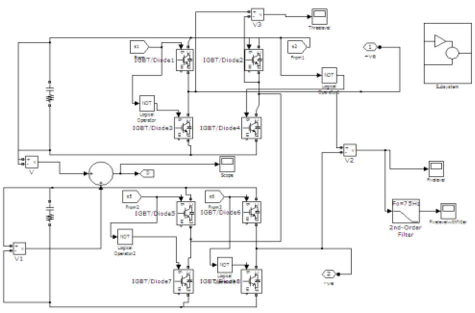


Fig 14 MATLAB/Simulink diagram of 5-level CHB-DSTATCOM

(F) Simulation Diagram of Control Circuit

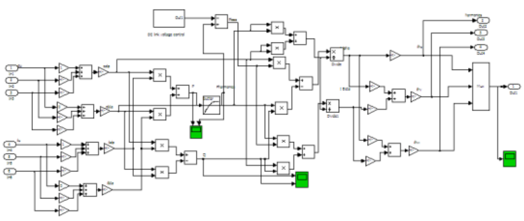


Fig 15 MATLAB/Simulink diagram of control circuit

(G) Simulation Diagram of PWM Modulation waveform Generation of PSCPWM and LSCPWM

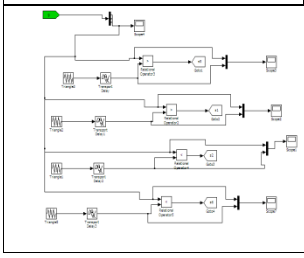
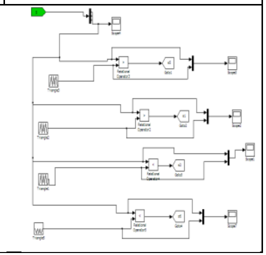
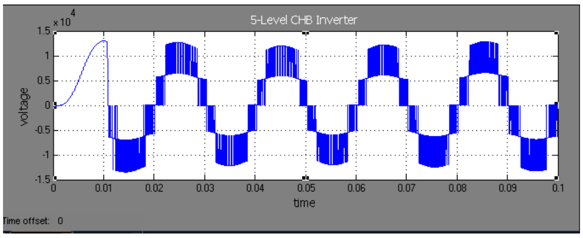
Phase Shifted Carrier PWM	Level Shifted Carrier PWM
	

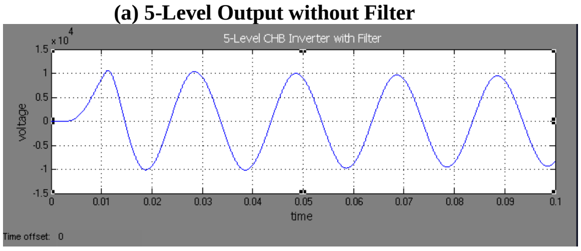
Fig 16 MATLAB/Simulink diagram of PWM waveform generation of PSCPWM and LSCPWM

Figures Shows the 5-Level CHB-DSTATCOM for compensation of Balanced and Unbalanced Linear and Non-Linear Loads, generating PWM modulation waveform by using PSCPWM and LSCPWM. At the unbalanced load, star connected impedance has taken. This impedance creates unbalanced currents at the distribution side, so that to introduce a STATCOM controller to compensate these unbalanced currents i.e. non-Sinusoidal Currents into Sinusoidal Currents at the distribution side then the STATCOM can be called as DSTATCOM. Here I am taking 3-phase voltage source with Linear and Non-Linear Load, here the load is three phase RLC branch. In between source to load a 5-Level CHB-DSTATCOM has taken in shunt with line.

Results:



(a) 5-Level Output without Filter



(b) 5-Level Output with Filter

Fig 17.Output Voltage Waveforms of 5-Level CHB Inverter

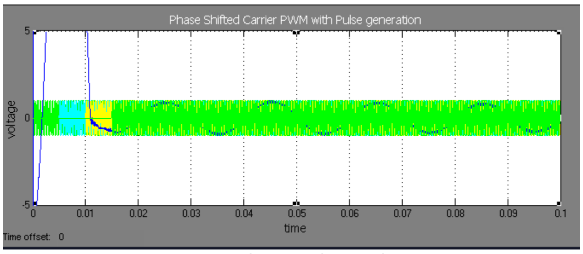


Fig 18 Carrier Phase Shift Waveform of 5-Level CHB Inverter

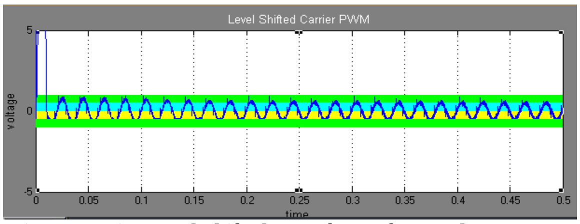


Fig 19 Carrier Level Shifted Waveform of 5-Level CHB Inverter

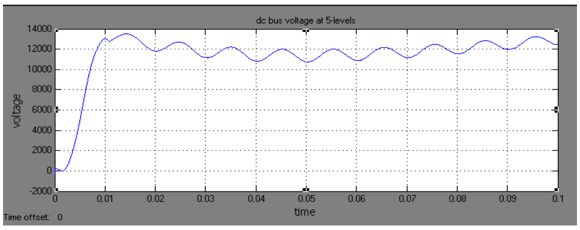


Fig 20 A 5-Level DC Bus Voltage

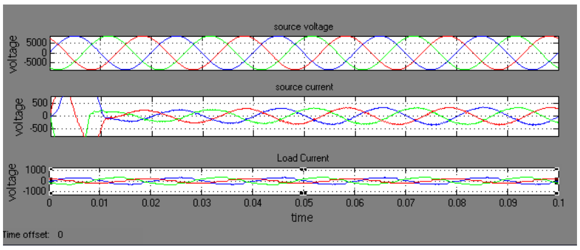
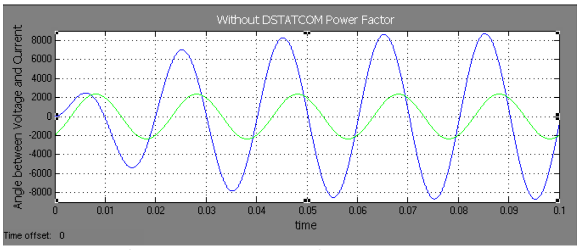
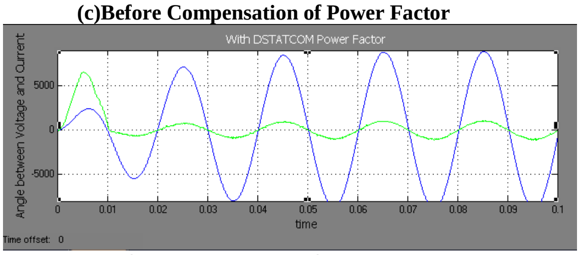


Fig 21 Voltage and Current Waveforms of 5-level CHB Inverter



(c)Before Compensation of Power Factor



(d) After Compensation of Power Factor

Fig 22 Power Factor Before and After Compensation

Fig 17 (a) Shows the output voltage waveform of without Filter and with the Filter of three phase of cascaded structure. The diagram shows cascaded multilevel structure can effectively reduce the voltage levels. (b) Which has been a sine wave with applying A filter and confirmed that THD of output voltage is 0.26%. Fig 18 and Fig 19 is the PWM Modulation Waveform Generation of a Phase Shifted and Level Shifted PWM. The simulation results confirmed that the operating frequency of the switching device and the loss can be effectively reduced when CHB structure is used.

Fig 20 is the modulation waveform of a 5-level CHB-DSTATCOM. The simulation results have confirmed that the DC bus voltages are stable. When the control method is used in this paper.

Fig 21 is the voltage and current waveforms of a 5-level CHB Inverter. In this source current and the load current is the different because of the presence of Harmonics. Appling a DSTATCOM at the source side, the unbalancing currents can be compensated and gives the sinusoidal waveform.

Fig 22 has confirmed that the Power Factor of load increased to 0.985 after the access of the DSTATCOM. So that, the load side current and the source side current are the same for all cases., which verifies satisfactory compensation effect of DSTATCOM.

V.CONCLUSION

DSTATCOM system is an efficient mean for mitigation of PQ disturbances introduced to the grid. DSTATCOM compensator is a flexible device which can operate in current control mode for compensating voltage variation, unbalance and reactive power and in voltage control mode as a voltage stabilizer. The latter feature enables its application for compensation of dips coming from the supplying network.

The simulation results show that the performance of DSTATCOM system has been found to be satisfactory for improving the power quality at the consumer premises. DSTATCOM control algorithm is flexible and it has been observed to be capable of correcting power factor to unity, eliminate harmonics in supply currents and provide load balancing. It is also able to regulate voltage at PCC.

The control algorithm of DSTATCOM has an inherent property to provide a self-supporting DC bus of DSTATCOM. It has been found that the DSTATCOM system reduces THD in the supply currents for non-linear loads. Rectifier-based non-linear loads generated harmonics are eliminated by DSTATCOM. When single-phase rectifier loads are connected, DSTATCOM currents balance these unbalanced load currents.

The simulation results show that the voltage sags can be mitigate by inserting D-STATCOM to the distribution system. The same analysis can be carried out for Double Line to Ground (DLG) fault and Three Line to Ground (TLG) fault also.

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VI. REFERENCES

[1]. Schauder C, Gernhardt M, E.stacey, et al. "Operation of±100Mvar VA STATCOM," IEEE Transactions Power Delivery, vol. 12, no.4, pp. 1805-1811, Oct. 1997.

[2] Li Xiaolu, Duan Xianzhong, He Yangzan, "Dynamic model of ASVGin unbalanced system, " Proceeding of the CSEE, vol. 19, no. 9, pp. 76-80, May. 1999.

[3] Ma Xiaojun, Jiang Qirong, Wang Zhonghong, Zang Kemao, "Unbalanced control based on individual phase for static synchronous compensator," Proceeding of the CSEE, vol. 21, no. 1, pp. 52-56, Mar. 2001.

[4] Zhu Yongqiang, Liu Wenhua, Qiu Donggang, Liu Bing, Lu Junfeng, "Simulation of balancing compensation of unbalanced load based on single phase STATCOM, " Power System technology, vol. 27, no. 8, pp. 42-45, Dec. 2003.

[5] Lai Jih-Sheng, Peng Fangzheng, "Multilevel converters－a new breed of power converters," IEEE Transactions on Industry Applications, vol. 32, no. 3, pp. 509-517, Mar. 1996.

[6]Yan Gangui, Liu Wenhua, Chen Yuanhua, Han Yingduo, "A generic PWM control method for flying capacitor inverter, " Proceedings of the CSEE, vol. 23, no. 6, pp. 35-40, Nov. 2003.

[7] Ding Kai, Zhou Yanking, Wang Zhan, Wu Zhichao, Zhang Yuen, "A novel hybrid diode-clamp cascade multilevel converter for high power application, " Proceedings of the CSEE, vol. 24, no. 9, pp. 62-67, Dec. 2004.

[8]Peng Fangzheng, Lai Jihsheng, "Dynamic performance and control of a static var generator using cascade multilevel inverters, " IEEE Transactions on Industry Applications, vol. 33, no. 3, pp. 748-755, Aug. 1997.

[9] Cengelci E, Sulistijo S U, Woo B O, et al. "A new medium-voltage PWM inverter topology for adjustable-speed drives, " IEEE Transactions on industry Applications, vol. 35, no. 3, pp. 628-637, Jun. 1998.

[10]Yoshii, T.; Inoue, S.; Akagi, H.; “Control and Performance of a Medium-Voltage Transformer less Cascade PWM STATCOM with Star Configuration”. Industry Applications Conference, 2006.41st, IAS Annual Meeting. Conference Record of the 2006 IEEE, vol. 4, pp. 1716-1723, Oct. 2006.

[11] Xu Xianglian, Zou Yunping, Ding Kai, Liu Fei, "Cascade Multilevel Inverter with Phase-shift SPWM and Its Application in STATCOM," The 30th Annual Conference of IEEE Industrial Electronics Society, Busan, Dec. 2004.

[12] Feng Jigui, Hu Cungang, Li Guoli, Li Xinqin, "Research on Carrier Disposition PWM Control Method for Three-level NPC Inverter, Power Electronics, vol. 42, no. 11, pp. 17-23, Oct. 2008.