Performance Evaluation of Adjustable Speed Drives Using Multilevel Inverter Based STATCOM

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Abstract-

Adjustable speed drives (ASD) employing induction motors are widely used in the industrials and process control in the form of varied applications such as fans, compressors, pumps etc. They are energy efficient and can result in substantial energy saving when properly installed. However, they inject high harmonic content into current drawn from the ac system. This paper deals with the application of a STATCOM for compensation of such loads. The MATLAB / Simulink based models are developed for adjustable speed drive loads. The analysis is carried out with and without STATCOM. The results shown in the paper prove that STATCOM can be used as a good harmonic filter. Cascaded multi-level converter based STATCOM (CMC-STATCOM), with a topology of modular-cascaded structure, has a wide prospect of applications in both transmission and distribution system. Under the background of application of STATCOM in high voltage power grid, there are many advantages of CMC-STATCOM compared with other kinds of STATCOM. On the basis of mathematical model of main topology, the states feedback decoupled reactive power control strategy based on the d-q coordinate system is studied in this paper, together with the application principle of carrier phase shift PWM modulation method in CMC. The balance of DC bus voltage is a key factor to the stable operation of devices In this paper, the hierarchical control method is used to achieve a balance of DC bus voltage, and it involves the DC bus voltage overall control and individual control of each cascade module.

Keywords-Cas caded H-Bridge, Multilevel Converter, STATCOM, Drives.

I. INTRODUCTION

Harmonic disturbances and their study has been a topic of research and today we can find a whole array of devices used to mitigate such problems. The ever growing use of power electronic based systems has aggravated the harmonics problem. These devices themselves require clean and good power quality but inject undesirable harmonics into the supply system as well as the neighboring loads. Literature review [1-6] indicate the problems, effects and solutions for harmonics in power systems. Different type of low voltage loads can also introduce harmonics in the power network and adversely effect on the overall performance and operation of the power system. In this paper, use of custom power device for harmonic reduction is studied.

There are three kinds of structure of the commonly used multi-level converter, which are flying-capacitor multi-level converter [6], diode-clamp multi-level converter [7], and Hbridge cascade multi-level converter. Cascaded multi-level converter has a lower output of waveform harmonic content, save more switching devices and has a more simple control system than other kinds of multi-level converter. Moreover its H-bridge modules have a compact structure, flexible configuration and reliable performance [8]-[10]. So the cascaded multi-level structure is used as converter topology of STATCOM in this paper.

Adjustable speed drives [7-12] employing the use of induction motors are widely used in process control in varied applications. The main benefit from ASDs is that their energy efficiency to the tune of 30-50%. This feature alone makes them very attractive to consumers. ASDs also improve system efficiency, equipment reliability, enhance product quality and reduce product waste and the noise level. However, the ASDs use power electronic devices for their switching operation which inject harmonics into the connected system. The increased penetration of these drives in electric utility system produces high harmonic content in current and voltage. The harmonic currents result in excessive heating in rotating machines. The harmonic currents, depending on their frequency, cause additional rotating magnetic fields in the motor. The magnetic field due to fifth harmonic, being the most prevalent tries to weaken the main field and rotates the motor in the opposite direction as the fundamental. Harmonic currents also cause overheating due to high-frequency eddy currents and hysteresis losses in the stator and rotor core and skin-effect losses in the windings. A comprehensive literature review is available on custom power devices which were invented by Hingorani [3] and are being used in distribution systems. Power quality problems in distribution system mainly include poor power factor, poor voltage regulation and harmonics. Also, additional problems due to neutral current and load unbalancing have to be studied and system design has to be through. The trend nowadays is shift focus from passive filters to active filters. Some problems related to passive filters include selective filtering, large sized inductors and capacitors are needed and they are prone to detuning and resonance problems. Custom power devices especially STATCOM can be used as very effective filter. It need not be designed to eliminate a particular harmonic, infact a STATCOM unit can be designed to eliminate all lower order harmonics introduced by the drive system. This paper discusses the application of STATCOM for reducing total harmonic distortion in supply current. The shunt compensator may be designed utilizing fast switching IGBTs switches[13,14,15]. The control logic is developed to produce an output current which when injected into the ac lines stops harmonic migration to the power source and alleviates the need for the source to supply reactive current. Good performance under system perturbations makes it an effective compensator. The best feature of this shunt compensator is that it can operate for lagging/ leading/ unity power factor loads and provide reactive compensation in both lead/ lag Vars.

II. MATHEMATICAL MODEL OF CMC-STATCOM

A. Main Topology

Main circuit topology of CMC-STATCOM is shown in Fig.1. In the figure, *Uc* is the output voltage of H-bridge cascaded multi-level converter; *Us* is the power grid voltage; *Ic* is the compensation current; *L* is the sum of connected inductance and equivalent inductance of the converter , and *R* is equivalent resistance of the converter.

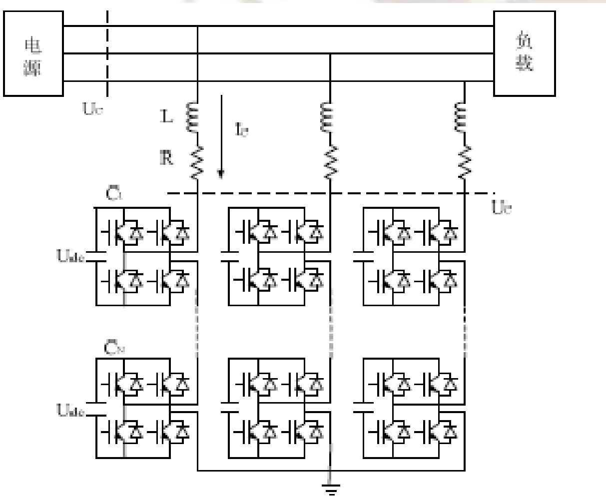

Figure-1Topology Of Main Circuit Of CMC-STATCOM

Cascaded multi-level converter is in parallel with power
line through a connected reactor. By adjusting the phase and
amplitude of AC output voltage of the converter appropriately, the circuit can absorb or sent out reactive current that meets the requirements, and achieve the purpose of dynamic reactive power compensation. This is the basic principle of CMCSTATCOM [13]. Voltage drop of the connected reactor has generated the compensation current, which is generated by the power grid voltage of access point of STATCOM and the output voltage of converter on both sides of the reactor, and then the connected reactor can also filter out some of the high harmonics generated by the converter. The output voltage of converter will lag a small angle compared to the power grid voltage in phase, so the converter can absorb a small amount of active power from the power grid side to compensate the internal loss of STATCOM, and stable the DC bus voltage.

B. Mathematical Model

Fig.2 shows the single-phase equivalent circuit of CMCSTATCOM.

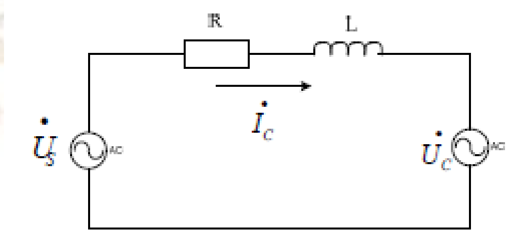

Figure-2 Single Phase Equivalent Circuit

Assuming the three-phase voltage of power grid is balance,
the expression of instantaneous value is:

$$\begin{cases} u_{sa} = \sqrt{2}U_s \sin(\omega t) \\ u_{sb} = \sqrt{2}U_s \sin(\omega t - \frac{2\pi}{3}) \\ u_{sc} = \sqrt{2}U_s \sin(\omega t + \frac{2\pi}{3}) \end{cases} \quad (1)$$

From the single-phase equivalent circuit in fig.2, it can be easily to get the relationship of three-phase voltage and current of compensator, as follows:

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

Change (2) from the three-phase coordinate model system
to the synchronous *d-q* coordinate system:

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

In (3), the transformation matrix *Cdq* is:

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

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

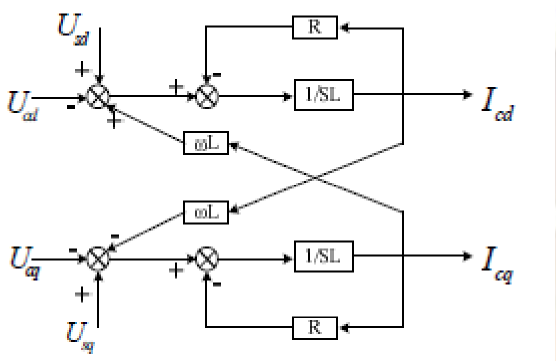

Figure-3 Equivalent structure diagram of CMC-STATCOM

III. CONTROL STRATEGY OF CMC-STATCOM:

Reactive Current Control

It can be seen from Fig.3 that the active current *icd* and reactive current *icq* couple each other because of the existence of connected reactor, so if one change, the other will change too, which is not conducive to reactive power control. The states feedback decoupled reactive power control method is used to introduce two intermediate control variables $x1$ and $x2$ which will control the active current *icd* and reactive current *icq* respectively, and PI controller is used to adjust the error, as follow:

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

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, i_{cd}^* and i_{cq}^* are reference values of active current and reactive current of the compensator. It can be seen from (5) that there is no coupling between the active current i_{cd} and reactive current i_{cq}, and then a real decoupling is achieved. The states feedback decoupled reactive power control block diagram of CMC-STATCOM is shown in Fig.4.

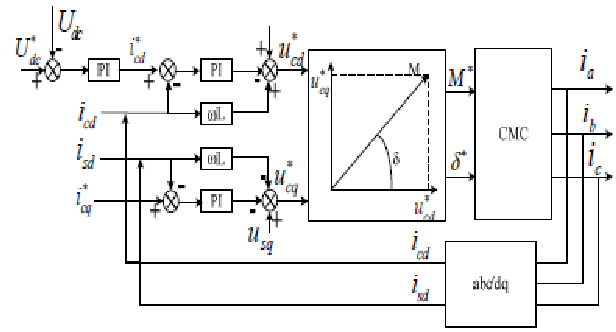

Figure 4. Diagram of states feedback decoupled control strategy

B. DC Bus Voltage Control

In [14] and [15], DC bus voltage balance of H-bridge cascade 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. DC bus voltage unbalance of converter will generate many adverse effects on the CMC-STATCOM. It will cause the harmonic distortion rate of converter output voltage increasing, and when the conditions become worse, the DC bus voltage of some H-bridge module will be higher, which will affect the safe operation of compensator.

In this paper, 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 feedback PI control is shown in Fig.4 to achieve a overall balance voltage. U_{dc} is the average value of DC bus voltage. Ideally, if there is a phase angle difference of 90^0 between each cascaded module of the CMC-STATCOM, no active power is consumed, and the capacitor voltage does not change. So by adjusting the phase angle between output voltages and output currents of the H-bridge modules, the DC bus voltage can also be corrected.

The implementing scheme of individual control of each cascade module is that a compensation voltage, which is same or opposite with the reactive current in phase, is superimposed on the reference voltage of DC bus of each cascade module, and U_{ai}^* is used to represent this compensation voltage, so we can adjust the active power that absorbed from the grid by each cascade module. Take module i of phase A into example, the DC bus voltage of this module is $U_{dc\text{-}ai}$, and we can get the reference voltage on the basis of the error between $U_{dc\text{-}ai}$ and U_{dc} which is the average value of DC bus voltage by PI regulator. Fig.5 shows the control block diagram.

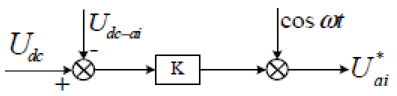

Figure 5. Diagram of individual control of each cascade module

IV. SYSTEM CONFIGURATION

Fig.6 shows the block diagram of the system with DSTATCOM connected in shunt configuration. Nonlinear load on the system is modeled in the form of adjustable speeddrive feeding induction motor load. STATCOM is modeled as a three-phase IGBT (Insulated Gate Bipolar Transistor) bridge based VSI (voltage source inverter) with dc bus capacitor at the DC link. Switching ripples need to be eliminated so small capacitors (C_c) have been used. The VSI bridge is connected to the three phase, three wire system via three input inductors (L_c, R_c). The role of these inductors may also be played by transformer. Adjustable Speed drive (ASD) operation includes a rectifier and a converter. The first mechanism is the converter operation which injects harmonic currents into the supply system by an electronic switching process. The second mechanism is the inverter operation which can introduce additional ripples into the DC link current. These ripples penetrate into the supply system side. The extent and the frequency of inverter-caused ripples depend on inverter design and motor parameters. The current analysis of the load current injected into the system shows a high THD of over 95% with a predominance of 5th and 7th harmonics. The most common three phase converter is a six-pulse unit. Its characteristic shows high 5th and 7th content.

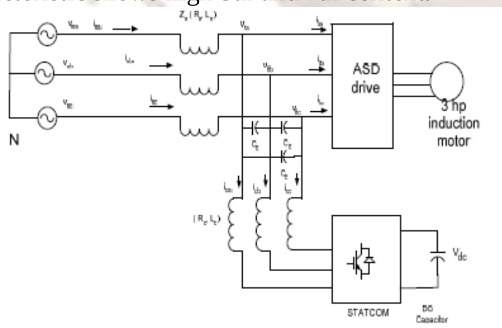

Fig.6 System block diagram with multilevel statcom

MODULATION METHOD

Carrier phase shift PWM and carrier phase disposition PWM are the relatively common two carrier pulse width modulation methods for multi-level structure. 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 wave. The former is more suitable for STATCOM based on H-bridge cascaded multi-level converter. If the carrier phase shift PWM is used, amplitude and frequency of each carrier signals are equal. So the voltage fundamental component outputted by different H-bridge modules is equal in theory. Additionally, the reactive current in a cycle frequency of each DC capacitor is the same so there is no trouble in balancing the output power between each Hbridge module, which will be conducive to the balance of the DC bus voltage control. In addition, the carrier and the modulation wave of each Hbridge module are modular structure, and the control system is simple and easy to implement. Carrier phase shift PWM technique is based on integrated natural sampling SPWM technology and multi-technology. The modulation principle is shown in Fig.7.

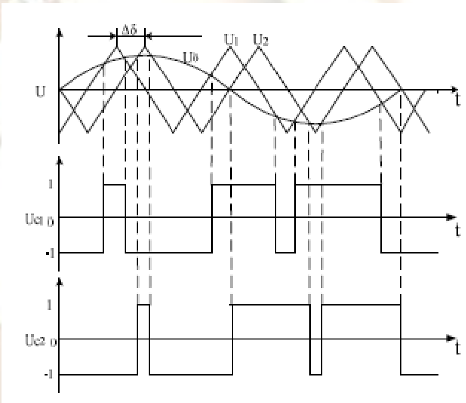

Fig 7. Principle of carrier phase-shift PWM technique

Each phase of the cascaded multi-level converter contains N H-bridge converter modules, in which the sine PWM technique with low switching frequency is used. The frequency modulation ratio k and the modulation signal *u0* have no difference for each H-bridge converter modules, and the triangular carrier phase has a difference of $\Delta\delta = 2\Pi / N \cdot k$ in phase. The H-bridge modules can work under a constant and lower switching frequency, but the equivalent voltage output frequency is N times of the carrier frequency. The output effect of the whole cascaded multi-level converter is equivalent to a SPWM converter with higher sampling frequency so that SPWM can be used in high-voltage occasions, and the converter output harmonic content is reduced effectively.

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IV MODELING AND SIMULATION

Various component models of the system are developed and simulated in MATLAB environment using Simulink and PSB toolboxes. The performance of the system is studied with and without the shunt compensator.

Performance of Adjustable Speed Drives

The harmonic analysis of the load current of adjustable speed drives shows the harmonic contribution from 5th, 7th, 11th, 13th, 17th 19th 23rd etc. The remaining higher order harmonics having contribution less than 1% are ignored. The analysis of the harmonic content is shown in Table –I. The total harmonic distortion of the load current is to the tune of 95% or greater when the compensator is not connected to the system. Fig.5 shows the response of STATCOM with adjustable speed drives. It shows three–phase supply voltages (v_s), supply currents (i_s), 'a' phase load current (i_{la},), STATCOM currents (i_{ca}, i_{cb}, i_{cc}) and dc link voltage (V_{dc}) along with reference value and torque and speed of the motor. It is observed that DSTATCOM is able to reduce harmonic content from 96.25% in load current to meet IEEE 519 standard for supply currents. STATCOM is able to maintain supply currents balanced and sinusoidal. The control scheme regulates dc link voltage (V_{dc}) to its reference value of 800V and thus establishes self-supporting dc bus of the STATCOM. The waveforms for voltages and currents for induction motor are shown for no load as well as when full load is put on the motor at t=0.7sec. Harmonic spectra and waveforms for the supply current and load current are shown are shown. It is observed that STATCOM is able to reduce the level of harmonics from 96.25% in load current to 1.9% THD in supply current. The harmonics in supply currents are less than 5% limits imposed by IEEE 519 standards.

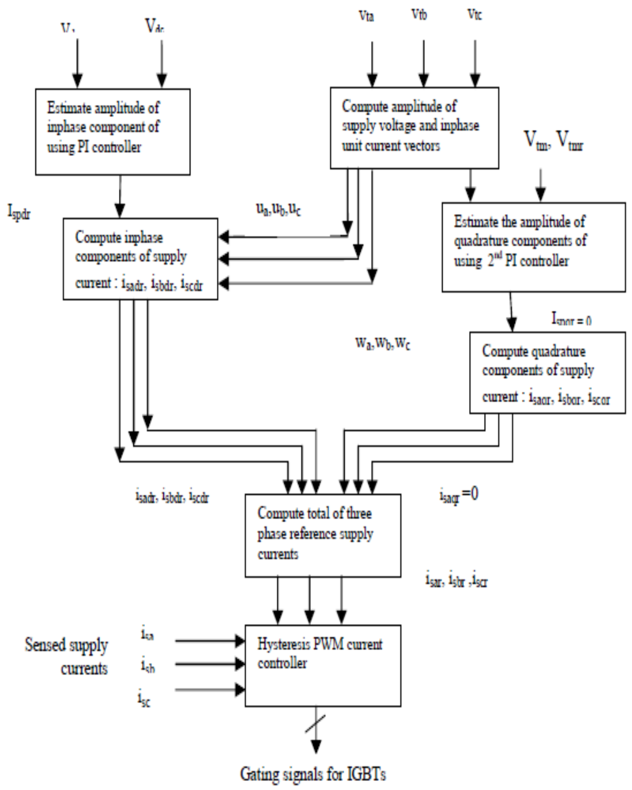

Fig.8 Representation of Control Algorithm

The MATLAB based model of the Multilevel based STATCOM for adjustable speed drives is shown below. The total Harmonic Distortion values are also calculated and shown below.

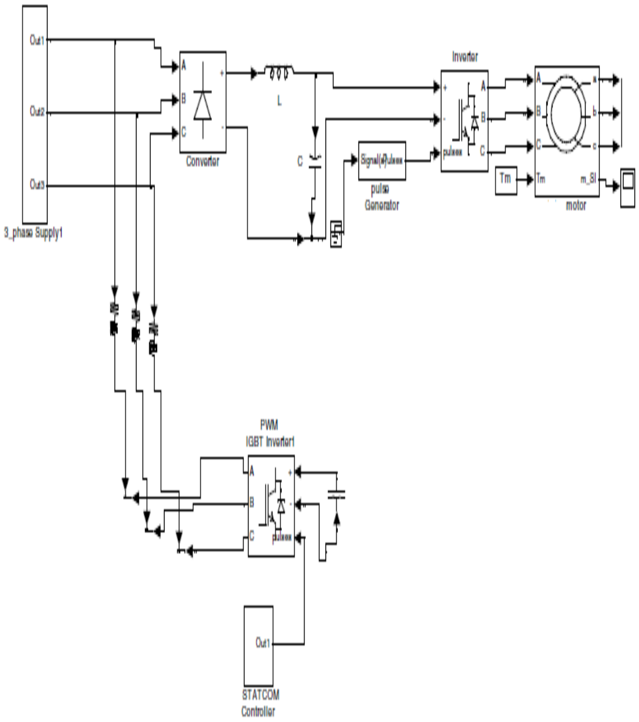

Fig.9 Matlab based model for system

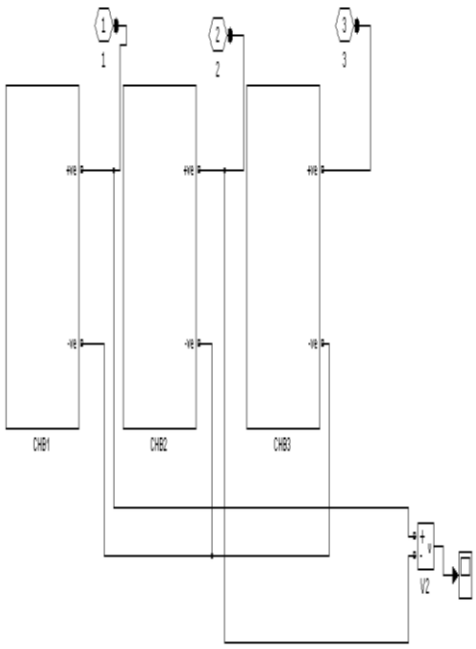

Fig.10 Multilevel STATCOM model

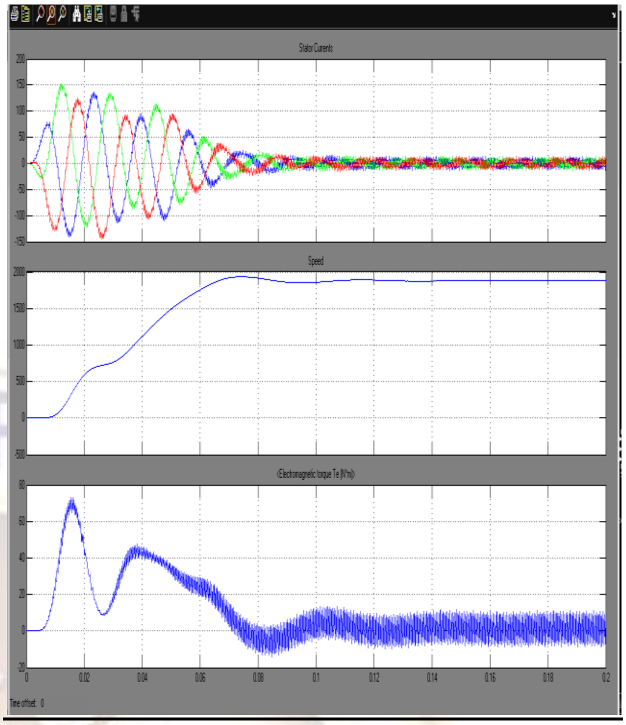

Fig-11 stator current, speed , and torque output wave forms

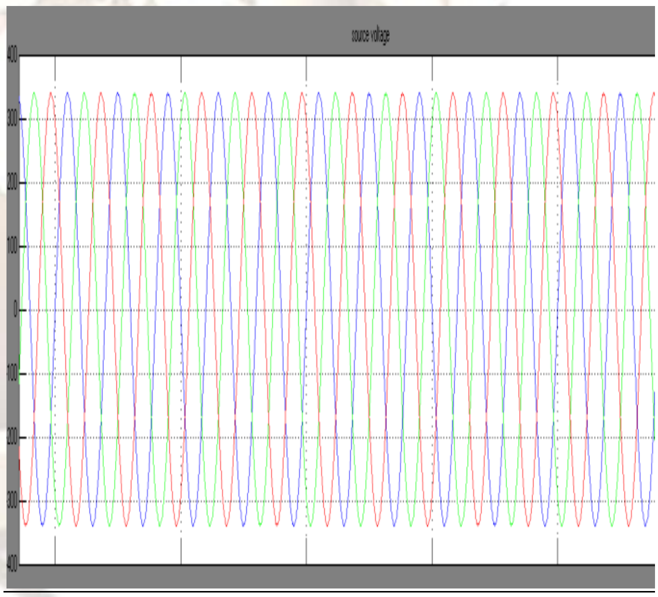

Fig.12 source voltage wave form

SIMULATION RESULTS

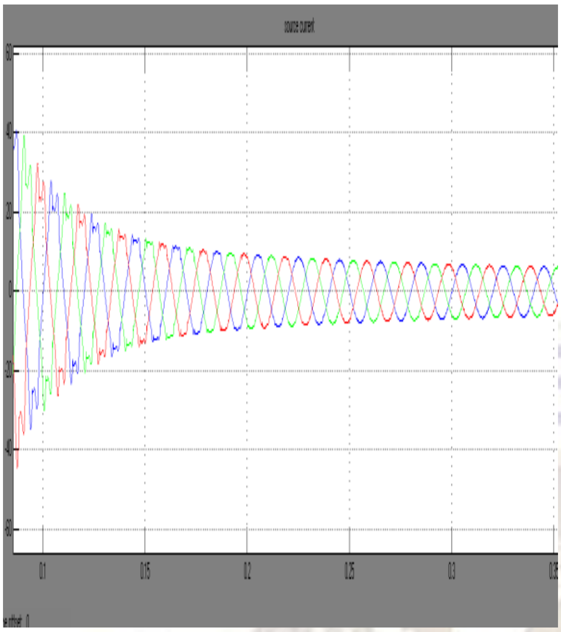

Fig.13 source current wave form

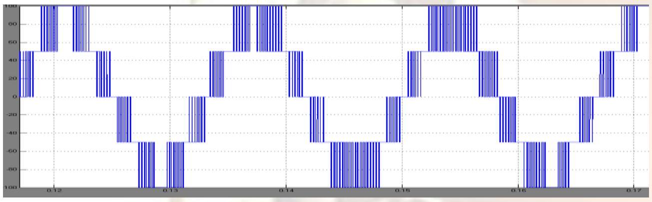

Fig.14 Multilevel inverter output voltage

VI Conclusion

Cascaded multi-level converter has a lower output waveform harmonic content, saves more switching devices and has a more simple control system than other kinds of multilevel converter. H-bridge modules which are used in the cascaded multi-level converter have compact structure, flexible configuration and reliable performance. Simulation results show that CMC-STATCOM has many advantages, such as good harmonic characteristics, reducing the output harmonic content while improving the capacity of equipment effectively, easy control system, quick response speed and so on. Because of its many technical advantages, the cascade multi-level converter becomes a research hotspot. The application of this topology in STATCOM is currently the focus of engineering practice, and has a broad application prospect.

The application of STATCOM as a compensator has been demonstrated with adjustable speed drive. Models have been developed for an adjustable speed drive system feeding a induction motor. It is observed that the content of harmonics injected by ASD is quite large. This harmonic injection in the neighboring loads can create problems. STATCOM in the form of a 3-leg VSI bridge has been modeled and controlled for harmonic reduction. Simulation analysis of the load currents with these nonlinear loads has been presented without / with STATCOM. The solution suggested in the form of STATCOM is better than a number of passive filters providing selective compensation. It is concluded that such a compensator can be effectively designed to meet the IEEE-519 standard for regulating the level of harmonics below 5% limit with speed drives.

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