CHAPTER 6

MULTIPHASE MULTILEVEL SSHSM SCHEMES

Multiphase multilevel inverters are used to provide multiphase variable voltage and variable frequency supply with appropriate PWM control, but new modulation techniques must be developed in order to lead these converters. The use of multiphase inverters together with multiphase AC machines has been recognized as a viable approach to obtain higher power ratings with current limited devices, by reducing the stator current per phase without increasing the voltage per phase. Furthermore, multiphase motor drives have several advantages over the traditional three-phase motor drives such as reduction of the amplitude and increase of the frequency of torque pulsations, and an improvement of the fault tolerance. In addition, multiphase motor drives offer a greater number of degrees of freedom compared with three-phase motor drives, which can be utilized for improving the drive performance.

In this chapter, SSHSM modulation principles are extended for multiphase cascaded voltage source inverters. An immediate benefit is that the switching frequency of power devices can be minimized. These modulations are derived from MSPWM. It is the most popular and widely used PWM technique because of their simple implementation in both analog and digital realization. The principle of MSPWM, true for a three-phase MI is also applicable to multiphase inverters. Thus, while operating in the linear region; maximum value of the modulation index of the MSPWM has the unity value. Modulator gain has the unity value while operating in the linear region and peak value of inverter output fundamental voltage is equal to the peak value of the fundamental sinusoidal signal.

The proposed modulation controller is modular structure, so that it can be easily extended to multiphase systems. In these modulations, the five phases are modulated independently in similar to the single phase systems. Each inverter cell is a standalone full bridge with PWM control, DC-link capacitors and gate drivers. So multiphase PWM control is viewed as a networked control system having (N-1)/2 hybrid modulators in each phase, and synchronized with phase references. The schematic diagram for a five-phase five-level CMI used to examine the proposed modulations is shown in Figure 6.1.

Four proposed SSHSM modulations such as HAPOD, HSCSM, HCBSVM, and HPSC are extended for multiphase inverter operation. Each phase SSHSM modulator consists of base MSPWM generation, base PWM circulation, and hybrid modulation controller. Base modulation pulses for each phase is identical, defined based on type of MSPWM used. FFPWM and SSP are to be synchronized with phase references, and same for all converter cells in each phase.

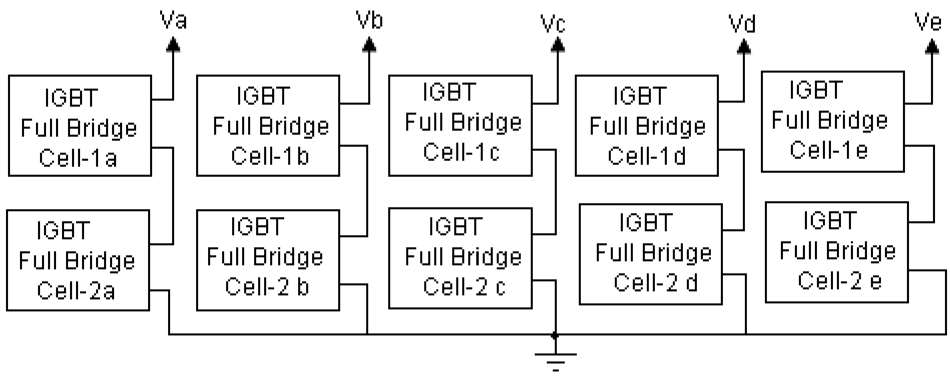


Figure 6.1 Schematic diagram of the five-phase five-level inverter

Five base PWM circulation modules are functioned in synchronized with their references. For HPSC modulation, PWM circulation can be omitted because it has the feature of inherent balanced loading among the cells. Identical HPWM controllers used for all phases and its function defined using simple combinational logic. Also, it should be noted that the number of PWM pulses highly increases when the number of phases are increased.

Simulation studies are also performed to show the validity of the proposed modulations under the conditions of fundamental frequency f_o=50 Hz, modulation index M=0.9, carrier frequency f_c=1750 Hz. The frequency modulation index is chosen as multiple of five to have symmetry in the output voltages.

6.1 MULTIPHASE SEQUENTIAL SWITCHING HAPOD MODULATION

A five phase five-level sequential switching HAPOD controller is shown in Figure 6.2. Five phase APOD pulses are generated throughout the comparison between the respective phase references and (N-1)/2 carriers. Modulation signals for all five phase inverter legs are equal to five sinusoidal fundamental signals. The phase difference between modulation reference signals are $\frac{2\pi}{5}$.

The amplitude of the phase references is modified based on $A_m = (N-1)\ M\ \frac{A_c}{2}$. The carriers are alternatively in phase opposition, it is phase shifted by 180^o from its adjacent carrier. Every phase APOD pulses are circulated independently using base PWM circulation controller. HMC in each phase combines FFPWM, SSP and APOD pulses for developing sequential switching HAPOD pulses for inverter operation.

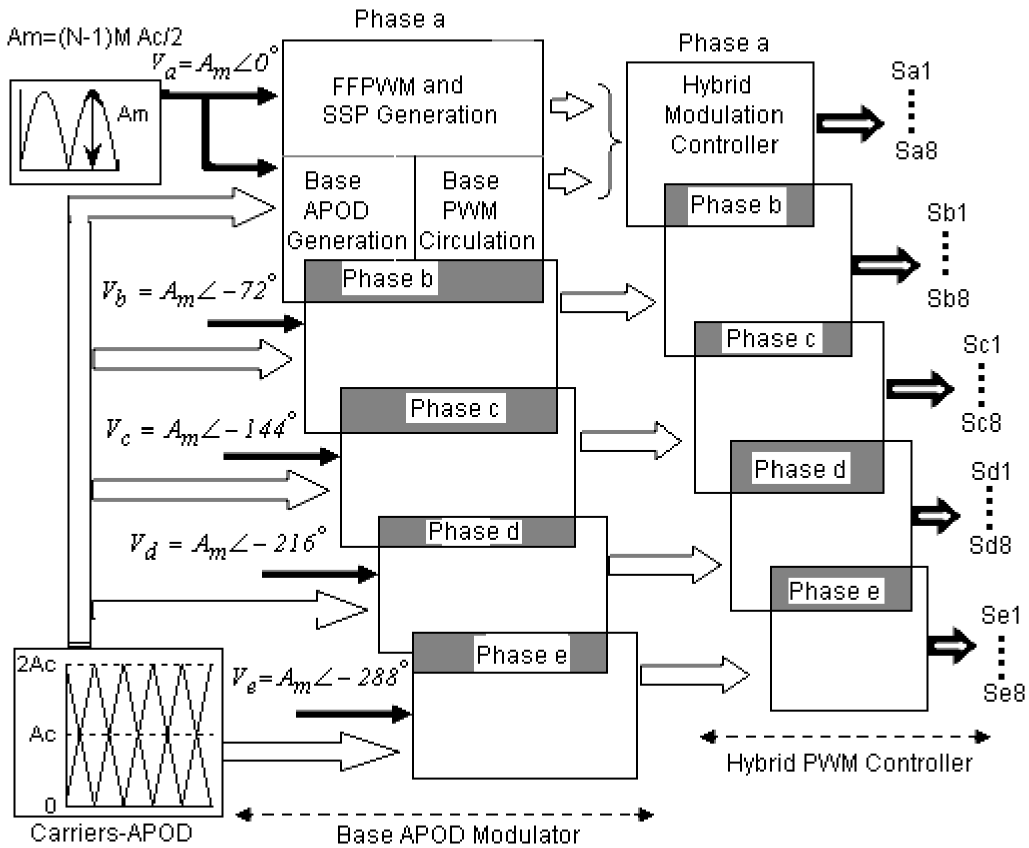
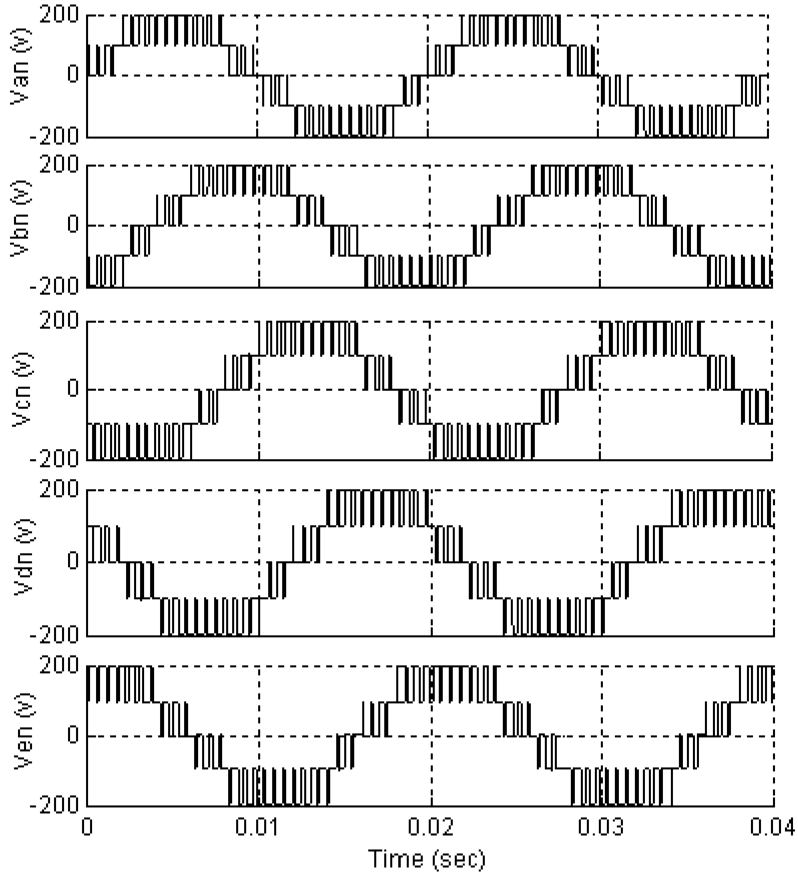
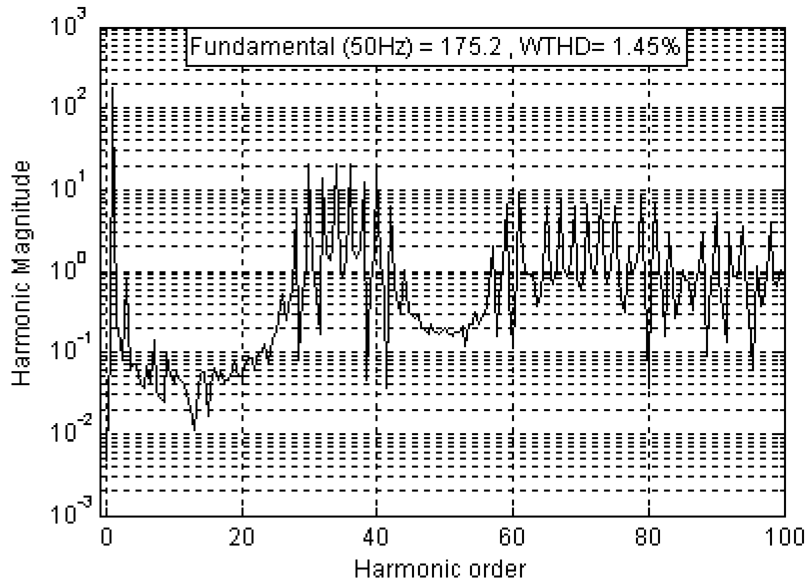


Figure 6.2 Scheme of five-phase sequential switching HAPOD modulation

The output phase to neutral voltage along with its harmonic spectrum is shown in Figure 6.3. Thus, the phase voltage from a three-phase and five-phase CMI are same when utilizing HAPOD. Over-modulation in multiphase inverter can play a more significant role comparing to three phase inverter because of its larger operating range. The phase current waveforms are shown in Figure 6.4. It is highly sinusoidal due to inherent feature of HAPOD and its THD value is 3.53% without any inverter output filter.

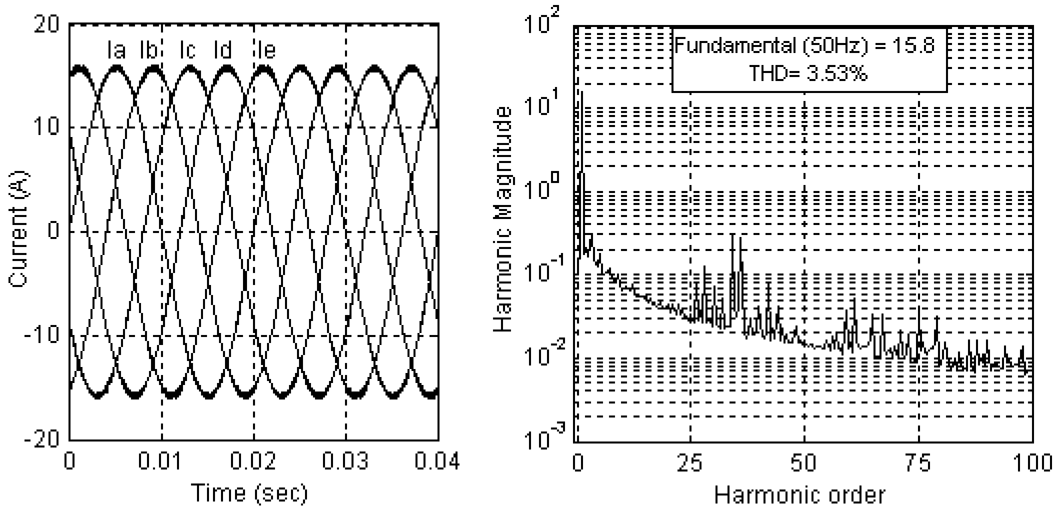


(a)



(b)

Figure 6.3 Five phase sequential switching HAPOD operation: (a) Phase voltage waveforms (b) Spectrum of the phase voltage



(a) (b)

Figure 6.4 Five phase sequential switching HAPOD operation: (a) Five phase current waveforms (b) Spectrum of the phase current

6.2 MULTIPHASE SEQUENTIAL SWITCHING HSCSM

The scheme of a five-phase five-level sequential switching HSCSM as shown in Figure 6.5, illustrates the multiphase HSCSM pulses generation. The principle of HSCSM, true for single phase systems, is also applicable for multiphase CMI. A single carrier having the frequency of f_c and amplitude of A_c is used for all the phases. The two modulation signals in each phase with DC bias difference of $-A_c$ are used for base SCSM generation. Thus, while operating in the linear region; maximum value of the modulation index of the SCSM has the unity value. Five phase sinusoidal references are to be synchronized, so that the inverter cells produce error free outputs. The phase difference between phase modulation signals are $\frac{2\pi}{5}$.

Two modulation signals in each phase are compared with a high frequency carrier, and two sets of five switching functions for inverter legs are obtained directly. HSCSM schemes are characterized by the presence of switching activity in each of the inverter legs over the carrier period, as long as peak value of the modulation signal does not exceed the carrier magnitude.

Base SCSM pulses are circulated in each phase using base PWM circulation controller for every switching period, to get resultant HSCSM circulation among the inverter cells. The HMC in each phase is used to combine SSP, FFPWM and the corresponding SCSM pulses, and then the HSCSM pulses are produced.

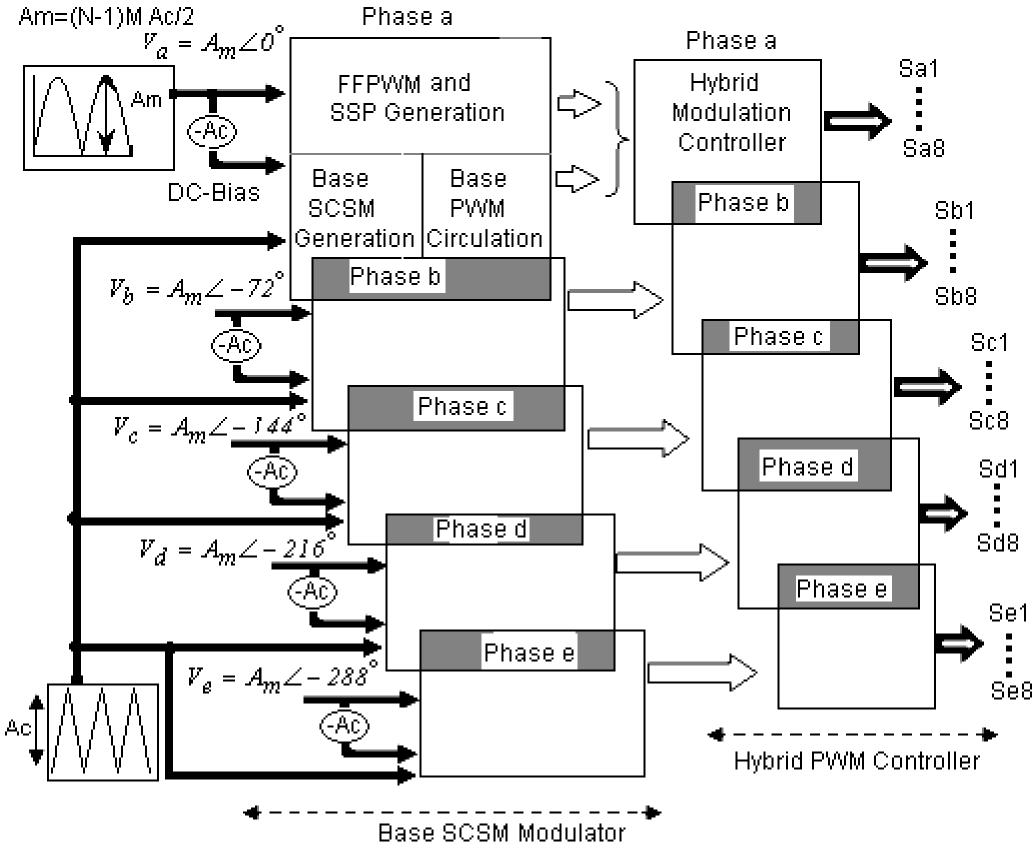
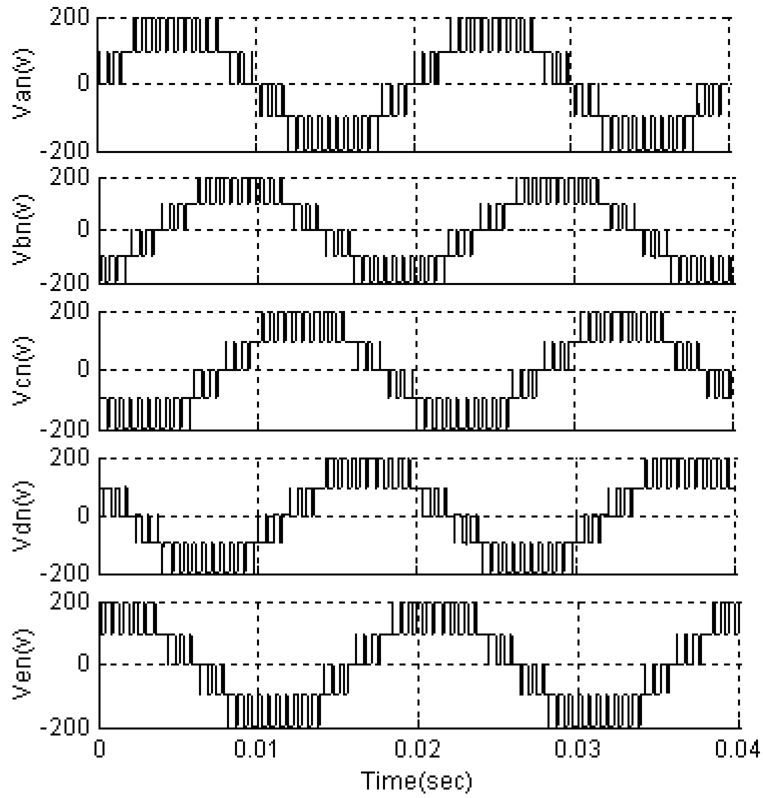
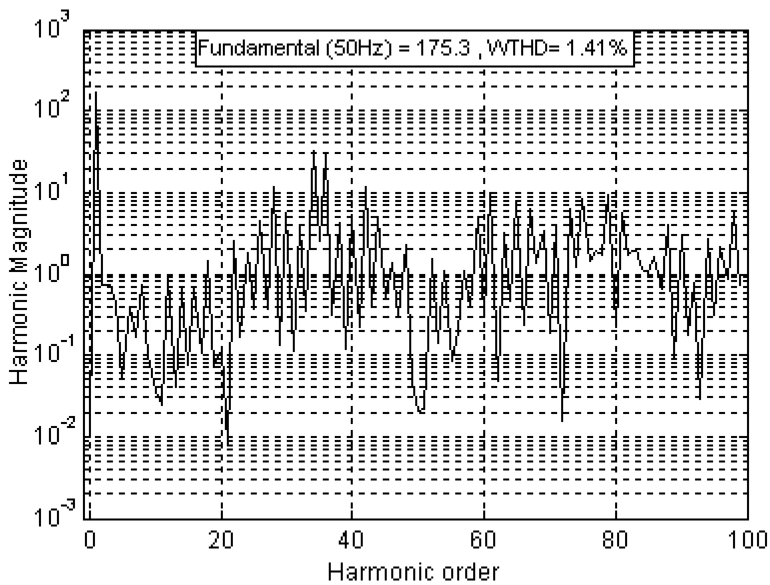


Figure 6.5 Scheme of five-phase sequential switching HSCSM

The phase voltages and its harmonic spectrum (phase a) for the five phase load, obtained using HSCSM, is shown in Figure 6.6, achieving a WTHD that is equal to 1.41%. It can be seen that the HSCSM strategy applied to each phase of the converter achieves high quality results with low conceptual complexity. In addition, the phase currents with its harmonic spectrum are shown in Figure 6.7, which is more sinusoidal with low magnitude current ripples. As seen in the spectrum, lower order harmonics are eliminated. The current THD is 4.05%.

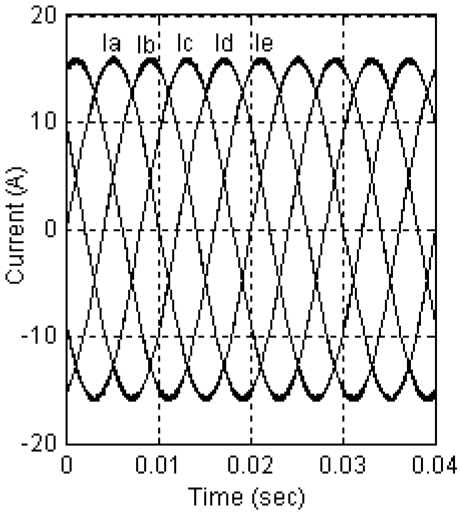


(a)



(b)

Figure 6.6 Five phase sequential switching HSCSM operation: (a) Phase voltage waveforms (b) Spectrum of the phase voltage



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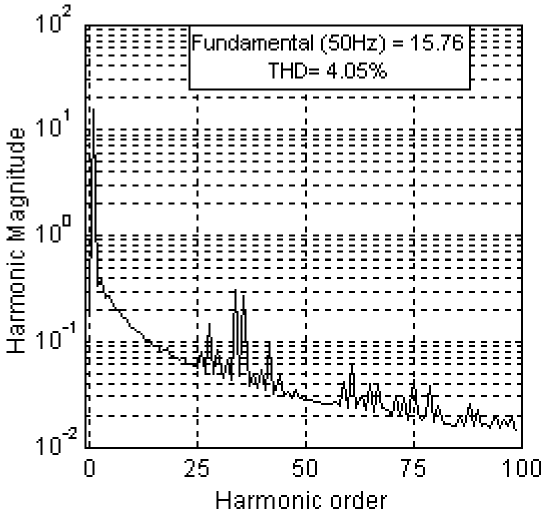


(b)

Figure 6.7 Five phase sequential switching HSCSM operation (a) Five phase current waveforms (b) Spectrum of the phase current.

6.3 MULTIPHASE SEQUENTIAL SWITCHING HCBSVM

Multiphase HCBSVM pulses are developed from base CBSVM for multiphase converters. CBSVM modulation signals are obtained using five fundamental sinusoidal signals (displaced in time by $\Theta = 2\pi/5$), which are summed with an appropriate off-set signal. These modulation signals are compared with a high-frequency carrier signal, and all five switching functions for inverter legs are obtained directly. Off-set signal represents a degree of freedom that exits in the structure of a carrier-based modulator and is used to modify modulation signal waveforms, and thus, to obtain different modulation schemes. The purpose of the addition of a common offset voltage to the multi-phase references will center the active space-vectors in the switching period, and hence match carrier modulation to get optimized SVM. The generalized structure of the HBSVM modulator, including offset signal calculator, is shown in Figure 6.8. The offset voltages for multiphase multilevel operation can be calculated as:

$$V_{off} = -\frac{\max(V_a, V_b, V_c, V_d, V_e) + \min(V_a, V_b, V_c, V_d, V_e)}{2} \tag{6.1}$$

$$V_k' = (V_k + V_{off} + V_{dc}) \bmod \left(\frac{2\,V_{dc}}{N-1}\right),\ k = a,b,c,d,e \tag{6.2}$$

$$V_{off}' = \frac{V_{dc}}{N-1} - \frac{\max(V_a', V_b', V_c', V_d', V_e') + \min(V_a', V_b', V_c', V_d', V_e')}{2} \tag{6.3}$$

The modulator signals for five-phase CBSVM can be represented as

$$V_k^* = V_k + V_{off} + V_{off}' \tag{6.4}$$

Using the resultant modified references and phase disposition carriers; the switching angles are then defined for CBSVM. The purpose here is to generate sinusoidal output phase voltages using CBSVM. Application of two neighbouring medium active space vectors together with two large active space vectors in each switching period makes it possible to maintain zero average value in the second plane, and consequently, providing sinusoidal output. The amplitude of the carrier signals are scaled to fit in to modulation range and its frequency is scaled to be much higher than the fundamental frequency. FFPWM and SSP pulses are to be synchronized with modified phase references, and same for all converter cells in each phase.

Each phase CBSVM pulses are circulated independently using base PWM circulation controller. HMC in each phase combines FFPWM, SSP and CBSVM pulses for developing sequential switching HCBSVM pulses for inverter operation. Thus, injection of the offset signal into five phase system leads to an increase of 5.15% in the DC bus utilization when compared to other SSHSM schemes. The operation of five-phase CMI is analyzed with

HCBSVM scheme, and the phase voltage waveforms with its harmonic spectrum are shown in Figure 6.9.

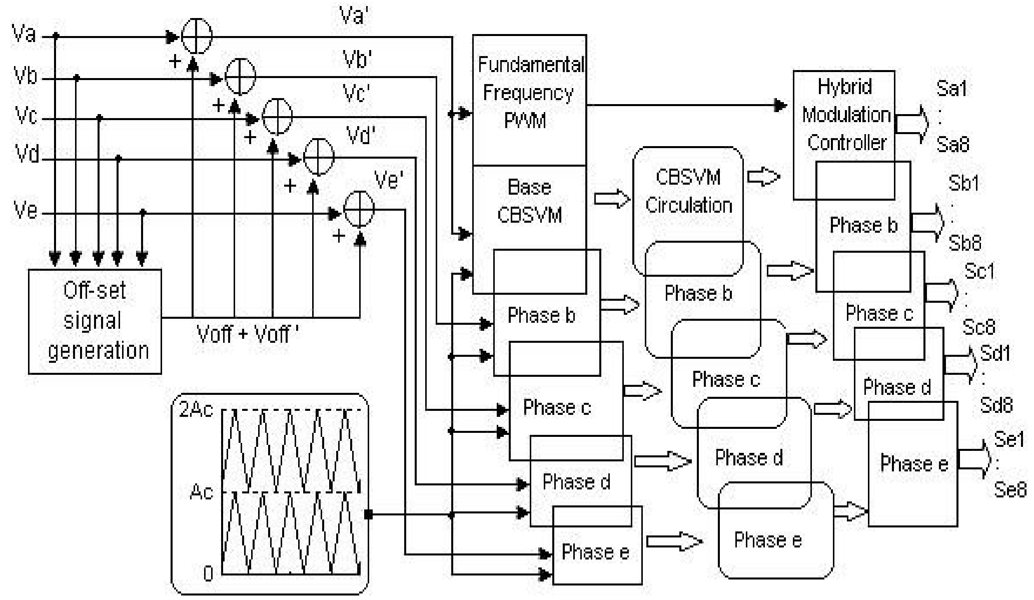
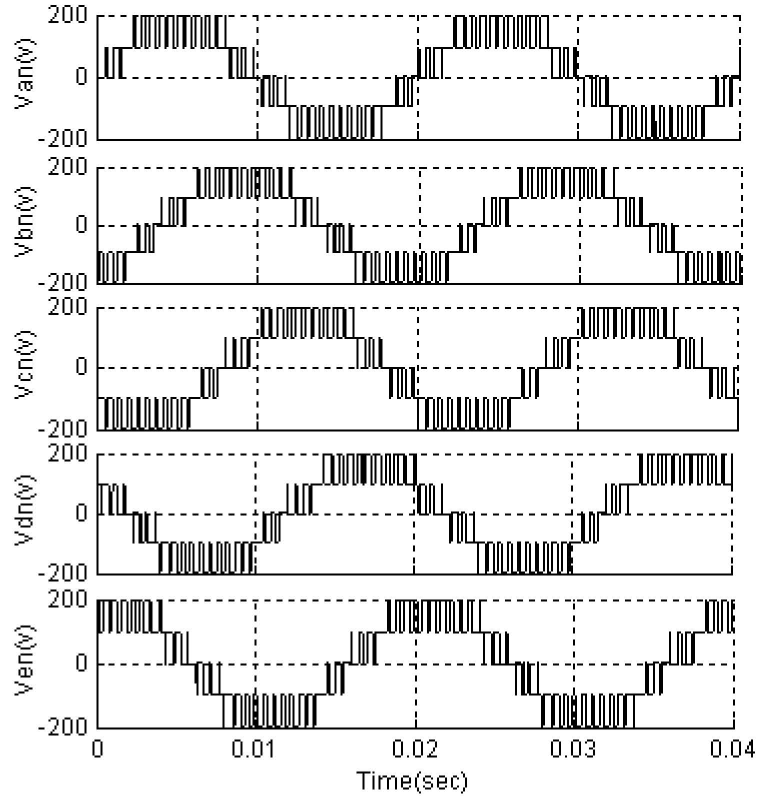


Figure 6.8 Scheme of five-phase sequential switching HCBSVM

The offset voltage addition reduces the peak of the phase reference voltages and hence the modulation index can be increased beyond the value of one without entering in to over-modulation. This increases maximum fundamental output voltage, and it does not affect the phase voltages, since the load is star connected with isolated neutral point.

The spectrum of the load current is shown in Figure 6.10 (b). As can be seen, it contains THD of 4.1% without inverter filter. Besides the switching harmonics around 1.75 kHz, it is clear that the other low frequency components are low amplitudes. This multiphase HCBSVM is a superset of the traditional CBSVM, and it inherits the merits of the SVM, such as high DC-link voltage utilization, low harmonic distortion and also the ability to optimize for lower power losses.



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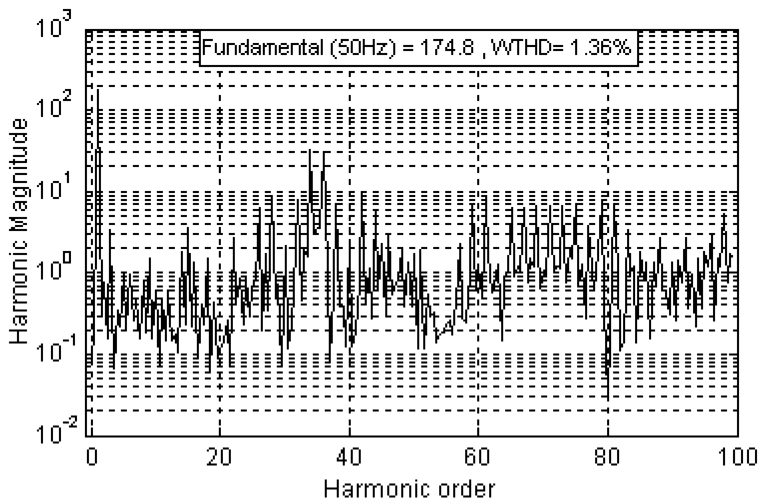
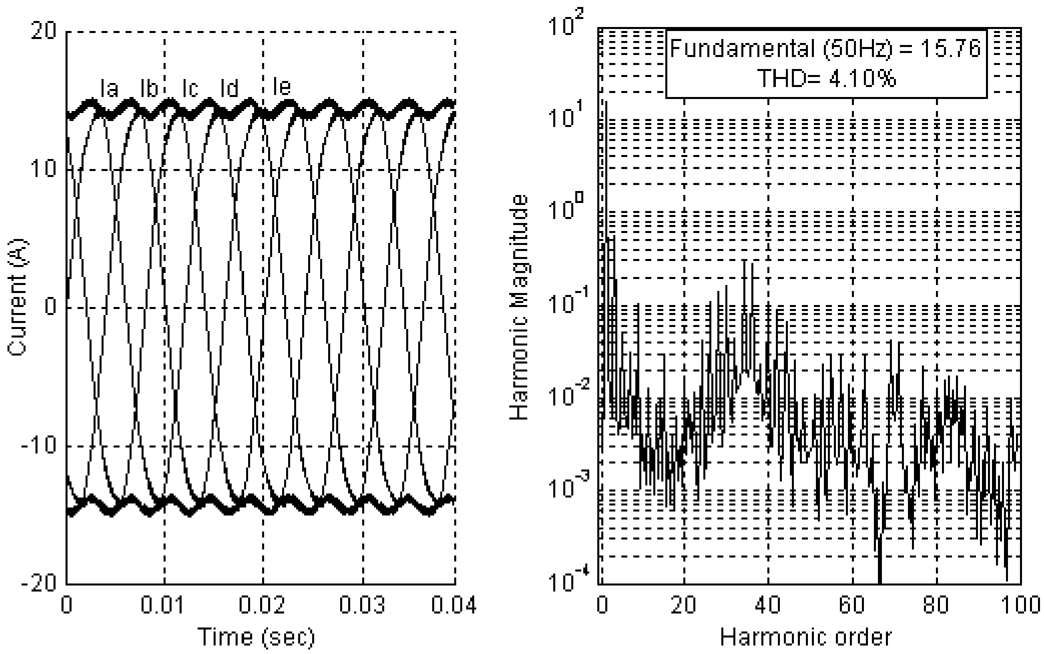


(b)

Figure 6.9 Five phase sequential switching HCBSVM operation: (a) Phase voltage waveforms (b) Spectrum of the phase voltage



(a) (b)

Figure 6.10 Five phase sequential switching HCBSVM operation: (a) Five phase current waveforms (b) Spectrum of the phase current

6.4 MULTIPHASE SEQUENTIAL SWITCHING HPSC MODULATION

Multiphase HPSC modulator consists of multiphase PSC modulator and hybrid modulation controllers. The general layout of the HPSC modulator for a five-phase CMI is shown in Figure 6.11. Modulation signals are five fundamental sinusoidal signals, which are displaced in time by $2\pi/5$. These modulation signals are compared with high frequency phase shifted carriers, and five-phase PSC modulation switching functions are directly obtained.

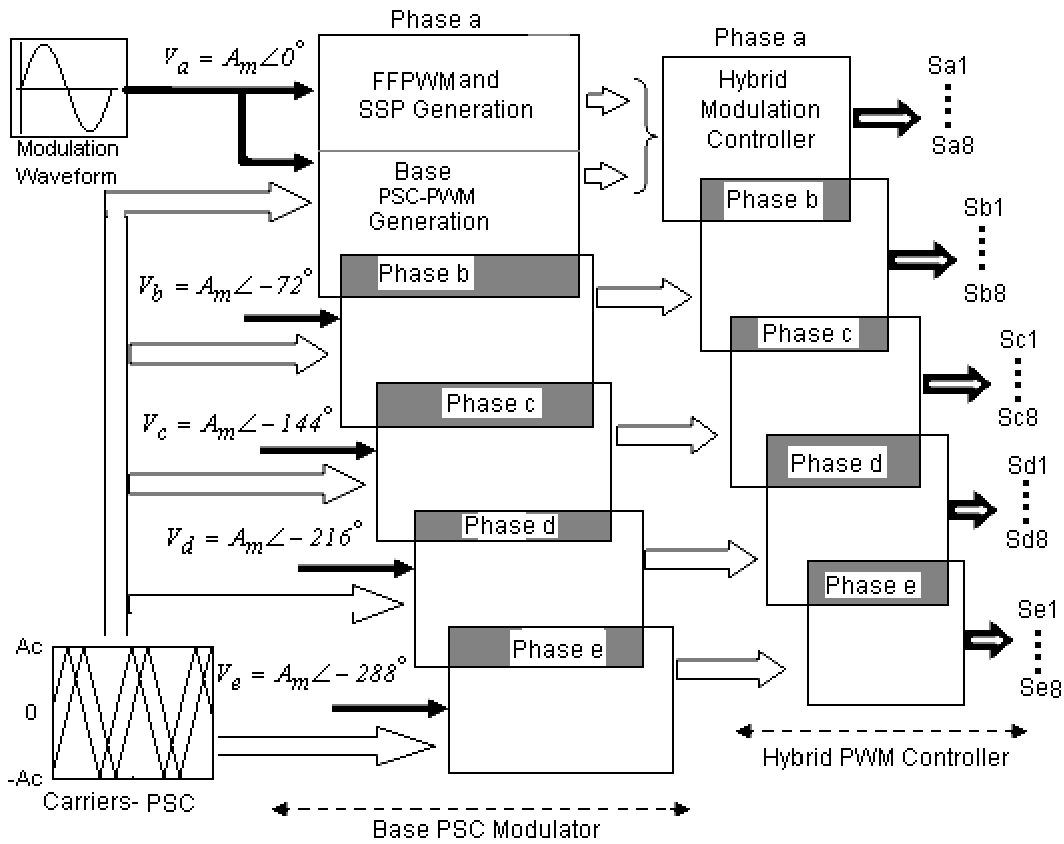
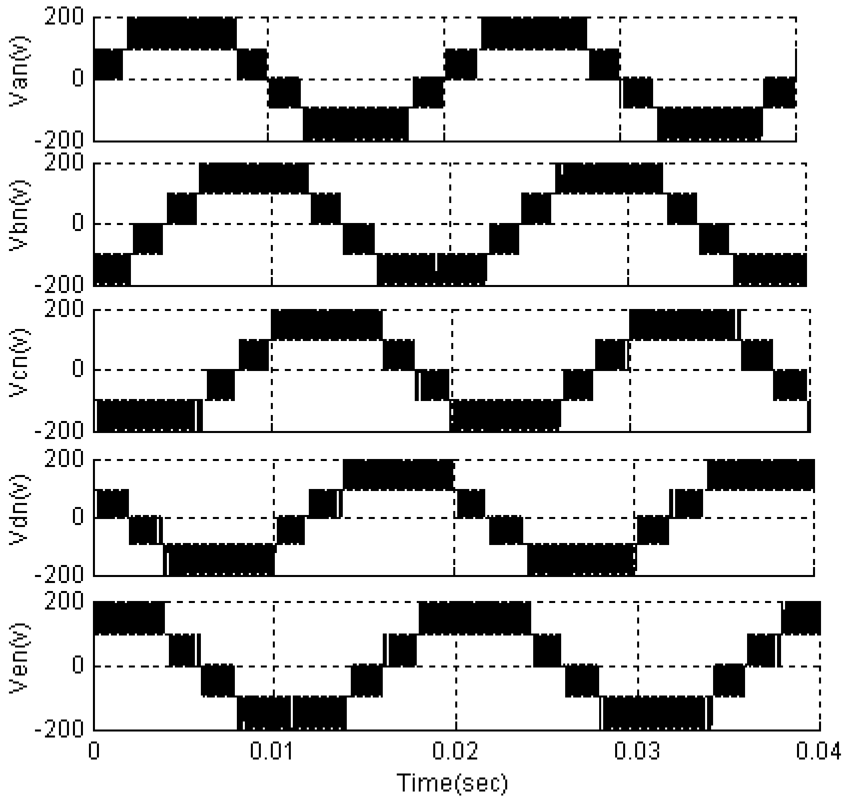


Figure 6.11 Scheme of five-phase sequential switching HPSC modulation

The duration of each pulse depends on the time that sine wave remains above the value of the carrier. These high frequency PSC-PWM pulses are sent to HMC. SSP and FFPWM pulses are produced in each phase, in synchronization with their phase references. HMC for each phase is used to combine the SSP, FFPWM and PSC pulses, and then HPSC pulses are generated for five-phase inverter operation.

The phase voltage waveforms with its harmonic spectrum are shown in Figure 6.12. This spectrum ensures that an increased bandwidth which is equal to four times the per unit frequency. This is the result of the phase shift induced which allows the cancellation of the switching frequency harmonics and the associated sidebands. The harmonic spectrum of phase current is also presented, it has very low THD.



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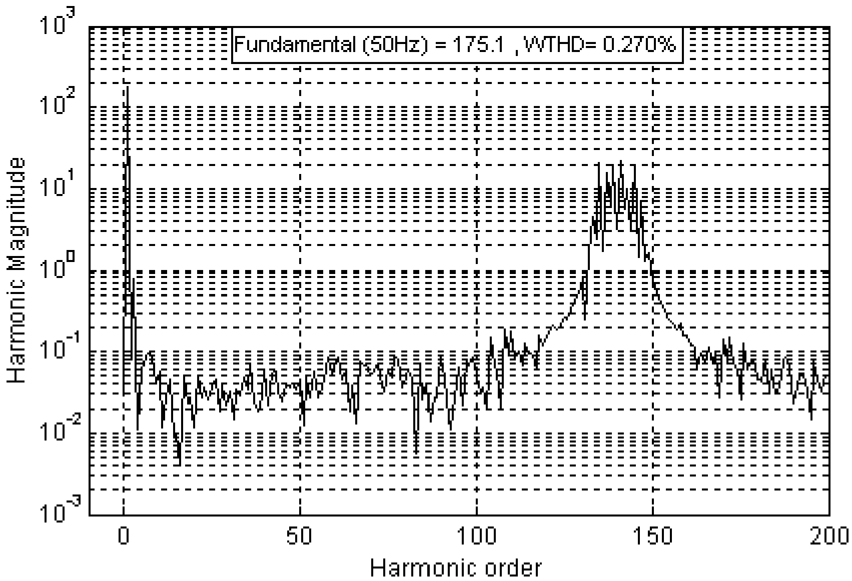
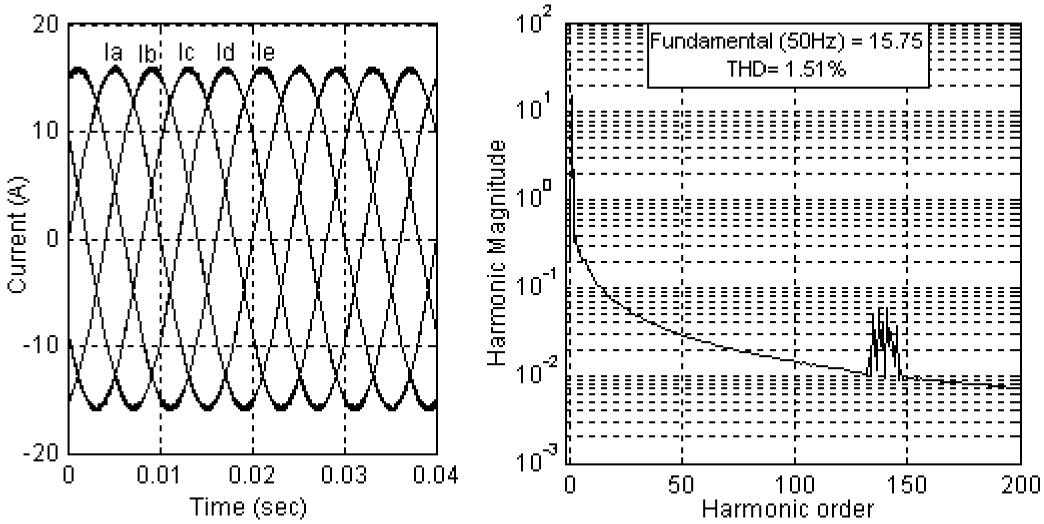


(b)

Figure 6.12 Five phase sequential switching HPSC operation: (a) Phase voltage waveforms (b) Spectrum of the phase voltage



(a) (b)

Figure 6.13 Five phase sequential switching HPSC operation: (a) Five phase current waveforms (b) Spectrum of the phase current

In this chapter, it has been demonstrated that the SSHSM techniques achieve high quality results for five-phase systems and for multiphase converters in general. These multiphase modulations are fully equivalent to previous MSPWM for multilevel converters, achieving good output performance with reduced switching losses. Also, compared with the SVM technique applied to multiphase multilevel converters, it can be noticed that the computational cost of the SSHSM technique becomes significantly lower when the number of phases increases because the SVM uses matrix calculations, leading to a high computational cost.

These modulations are having simple algorithm, a tendency for a low common mode voltage, good voltage quality with no simultaneous two-level switching. At the same time, equal loading of the modules are achieved. If the five phase load is balanced, and the switching frequency and the average DC current loading are the same for inverter cells, then the conduction and switching losses are the same.