Chapter 8

Seven-Phase Voltage Source Inverter
Supplying Seven-Phase Series Connected
Three-Motor Drive System

8.1 INTRODUCTION:

Modelling and control issues of a Seven-phase inverter feeding a Seven-phase machine are elaborated in chapter 7. This chapter is devoted to the control of a Seven-phase voltage source inverter feeding Seven-phase three-motor drives i.e. three seven-phase motors whose stator windings are connected either in series or in parallel and the group of these motors are supplied from one seven-phase VSI. Since vector control of any multi-phase machine requires only two stator current components, the additional stator current components are used to control other machines. It has been shown that, by connecting multi-phase stator windings in series/parallel with an appropriate phase transposition, it is possible to control independently all the machines with supply coming from a single multi-phase inverter. One specific drive system, covered by this general concept, is the Seven-phase series-connected/parallel-connected three-motor drive, consisting of three Seven-phase machines and supplied from a single Seven-phase voltage source inverter. This chapter investigate the control methodology of the seven-phase VSI supplying the three-motor drive system and controlling them independently.

Space vector PWM techniques have been reported for a Seven-phase VSI for single motor drive where attempts have been made to generate sinusoidal waveform. Considering a Seven-phase system there exist three orthogonal planes namely $d-q$, $x_1-y_1$ and $x_2-y_2$. Unwanted low-order harmonics are generated in the output of a Seven-phase VSI when the space vectors of $x_1-y_1$ and $x_2-y_2$ planes are not eliminated completely and they result in distortion in stator current and losses in the machine having sinusoidal mmf distribution. In case of concentrated winding machine, low order harmonic currents are injected along with the fundamental to enhance the torque production.

A modulation technique termed as “unified voltage modulation” scheme is proposed for a three-phase voltage source inverter in [add reference]. This method is based on the calculation of gating time of each inverter leg from the information of sampled reference voltages. This method is adopted for phase number five and six as detailed in the previous chapters. The similar modulation approach is used in this chapter for a Seven-phase VSI.
supplying three series-connected Seven-phase machines. It is important to note here that the control technique of the inverter is independent of type of stator winding connection i.e. series or parallel. Hence only series connection is considered here, the same principle applies to the parallel connection as well. The gating time of inverter switches are obtained directly from sampled reference voltages; modulating the inverter for generating appropriate voltages for independently controlling the series-connected Seven-phase machines. Complete algorithm is provided with their validation using simulation.

8.2 SEVEN-PHASE SERIES-CONNECTED THREE-MOTOR DRIVE

When the phase variable equations are transformed using decoupling matrix, four sets of equations are obtained, namely \(d-q\), \(x_1-y_1\), \(x_2-y_2\) and zero sequence. In single Seven-phase motor drives, the \(d-q\) components are involved in actual electromagnetic energy conversion while the \(x_1-y_1\) and \(x_2-y_2\) components increase the thermal loading of the machine. However, the extra set of current components \((x_1-y_1\) and \(x_2-y_2\) available in a Seven-phase system is effectively utilised in independently controlling two additional Seven-phase machines when the stator windings of three Seven-phase machines are connected in series/parallel and are supplied from a single Seven-phase VSI. Reference currents/voltages generated by three independent vector controllers, are summed up as per the transposition rules and are supplied to the series-connected/parallel-connected Seven-phase machines. Block diagram of the three-motor drive systems is illustrated in Fig. 8.1 for series connection and the connectivity matrix is in table 1.

![Fig. 8.1 Seven-phase series-connected three-motor drive structure](image-url)
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Table 1: Connectivity matrix for the seven-phase series connected three-motor case.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>M2</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>7</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>M3</td>
<td>1</td>
<td>4</td>
<td>7</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>

The scheme of series-connected Seven-phase three-motor drive discussed in the literature [Jones thesis (2005)] utilizes current control in the stationary reference frame. However, if current control in the rotating reference frame is to be utilized, appropriate PWM scheme for Seven-phase VSI needs to be developed to generate voltage references instead of current references. The principle of control decoupling of three Seven-phase series-connected machines lies in the fact that the \(d-q\) voltage/current components of one machine becomes the \(x-y\) voltage/current components of the other machines and vice-versa.

Since Space vector PWM offers higher dc bus utilization, the thesis focuses on the development of appropriate space vector PWM for three-motor drive system in addition to other PWM offering high dc bus utilisation.

8.3 PWM FOR SEVEN-PHASE VSI SUPPLYING THREE-MOTOR DRIVE SYSTEM

The following section elaborates PWM schemes employed for Seven-phase three-motor drive;

1. Carrier based pulse width modulation scheme
2. Offset addition pulse width modulation scheme
3. Time equivalent space vector pulse width modulation (TESVPWM) scheme
4. Artificial neural network based space vector pulse width modulation.

8.3.1 CARRIER BASED PULSE WIDTH MODULATION SCHEME

The PWM signal is generated by comparing a sinusoidal modulating signal with a triangular (double edge) or a saw-tooth (single edge) carrier signal. In a Seven-phase three-motor drive, the references for each motor is generated separately from three vector controllers are then summed according to the transposition rules. The summed voltages serve as modulating signals. These modulating signals are compared with the high frequency carrier signals (triangular) and the gating pulses are generated for the inverter.
The dc bus voltage utilization is 0.5 p.u. and because of the sequential nature of control, each motor utilizes only one third of this value. It is important to highlight that this is the major disadvantage of the series-connected drive scheme.

Matlab/Simulink model is developed for carrier-based PWM and the simulation results are illustrated in Fig. 8.4. Since the motor is supplying three motor connected in series and the value of DC link voltage is $V_{dc}$ set to 3 p.u. The switching frequency is kept 5 kHz. The fundamental frequency is kept 50 Hz for all the three motors. As it is the case of
Seven-phase VSI supplying three motor drive system and all the motors are operating at same frequency. The peak of carrier wave has taken here as $\pm 0.5V_{dc}$.

Simulation results are shown in Fig. 8.4(a) shows the filtered output voltage and Fig. 8.4 (b) shows the harmonic spectrum for phase 'a' voltage. Harmonic spectrum shows that inverter output voltage contains single components at 50 Hz with a magnitude of 1.062 p.u. rms (1.50 p.u. peak).
Harmonic spectrum of phase ‘a’ voltage in three planes are shown in Fig. 8.5. The inverter d-q axis phase ‘a’ voltage in Fig. 8.5 (a) shows that it contains a perfectly sinusoidal single component at 50 Hz frequency with a magnitude of 0.3425 rms p.u. (0.4844 peak). Fig. 8.5 (b) shows single component at 50 Hz frequency with a magnitude of 0.3422 rms p.u. (0.4839 peak) in x1-y1 axis and Fig. 8.5 (c) shows single component at 50 Hz frequency with a magnitude of 0.3425 rms p.u. (0.4844 peak) in x2-y2 axis. Thus each machines are being controlled independently.

### 8.3.2 OFFSET ADDITION PULSE WIDTH MODULATION SCHEME

It is well known that the addition of offset voltages in references voltages in a three-phase system lead to enhanced output [8.22]. The same concept is extended for multi-phase system in the literature. The same concept is extended to Seven-phase drive system with series-connected three-motor system in this chapter.

An offset voltage is injected into the summed leg voltage references, which are then compared with a triangular carrier wave to generate switching pulses for the power semiconductor devices. The offset voltage is given by

\[
V_{\text{offset}} = -\frac{V_{\text{max}} + V_{\text{min}}}{2} \quad V_{\text{max}} = \max\{v_1, v_2, v_3, v_4, v_5, v_6, v_7\} \quad V_{\text{min}} = \min\{v_1, v_2, v_3, v_4, v_5, v_6, v_7\}
\]

In essence this offset injects 7n, n=1, 2, 3... harmonics. This causes the modulating signal peak to reduce offering more room to enhance the modulation index. Once again this is
validated using Matlab/Simulink model. For simulation purpose, all the simulation parameters are kept same as in section 8.3.1. The block representation of the offset addition scheme is shown in Fig.8.6. The reference quantities are represented by $^\ast$, thus three set of references are generated and are summed as per the transposition rule to formulate the overall reference leg voltages. The offset is then added to this signal to produce overall modulating signals. The modulating signals thus generated are compared with the high frequency carrier to yield switching signals. The switching frequency of inverter is set to 5 KHz and the fundamental frequency of all the references is kept at 50 Hz.

Fig. 8.6 Block representation of the offset addition scheme

Due to phase transformation in the series connection their summation will yield three times the individual value. However, offset addition will actually modifies the total inverter leg voltage references so that the maximum leg voltage references may appear in a different legs. This has been investigated by simulation in details.
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Fig. 8.7 Simulation results without increasing the modulation index.
Simulation results shown in Fig.8.7 (a) shows the Components of the leg voltages reference for inverter leg A with the resulting modulating signal obtained & Fig. 8.7 (b) depicts inverter phase output voltage and its spectrum. The output voltage spectrum shows that fundamental is actually composed of single component at a frequency of 50Hz with magnitude of 1.062 p.u. rms (1.50 p.u. peak). By decomposing the instantaneous inverter phase voltages, using Clark’s transformation for a Seven-phase system obtains the inverter phase voltages in \( \alpha-\beta \) plane, \( x_1-y_1 \) plane and \( x_2-y_2 \) plane. The \( \alpha \) axis components shown in Fig.8.7(d) from which it follows that the 50 Hz fundamental appears in \( \alpha-\beta \) plane with magnitude of 0.3425 rms p.u. (0.4844 peak) and 50 Hz fundamental appears in \( x_1-y_1 \) plane with magnitude of 0.3422 rms p.u. (0.4839 peak) shown in Fig. 8.7(e). Fig. 8.7(f) shows that 50 Hz fundamental appears in \( x_2-y_2 \) plane with magnitude of 0.3425 rms p.u. (0.4844 peak).

These three components control independently three Seven-phase machines connected in series with appropriate phase transposition. Since the total modulating signal in Fig.8.13 (a) is below the limiting value of 1.5, it is possible to increase the individual references of the three machines above 0.5 p.u. only part of this increase is possible due to offset addition, while the remainder of the possible increase is associated with the fact that the three motor drive actually does not require three times of the dc link voltage.

By performing trial and error procedure, it has been established that the maximum value for the reference is 0.685 p.u. (peak). The inverter leg A voltage reference and the output phase voltage spectrum are shown for this condition in Fig.8.8 (a) & (b). However, the limiting value of \( \pm 1 \) p.u. actually appears in the modulating signals of leg E and leg B this being the consequence of the offset addition. The peak value of leg A is an intermediate value, while the peak values of leg C and D are the same and the lowest.
The α axis components shown in Fig. 8.8(a) from which it follows that the 50 Hz fundamental appears in α−β plane with magnitude of 0.4702 rms p.u. (0.6649 peak) and 50 Hz fundamental appears in x1−y1 plane with magnitude of 0.4698 rms p.u. (0.6644 peak) shown in Fig. 8.8(b). Fig. 8.8 (c) shows the components of the leg voltages reference for inverter leg A with the resulting modulating signal obtained & Fig. 8.8 (d) depict inverter phase output voltage and its spectrum i.e. single component at a frequency of 50 Hz with magnitude of 1.4522 p.u. rms (2.0538 p.u. peak). Fig. 8.8(e) shows that 50 Hz fundamental appears in x2−y2 plane with magnitude of 0.4705 rms p.u. (0.6654 peak). Fig. 8.8(f) shows the equivalent modulating signals.
8.3.2.1 GAIN IN DC BUS UTILIZATION DUE TO OFFSET ADDITION

The dc link voltage has been set to three times the value required for a single motor drive in simulation. With such a dc voltage it is possible to increase the modulation index upto 0.685. It is shown in Fig. 8.9 (a) that maximum value appears at different phase shifts without transposition is 3.8989 peak. The Fig. 8.9 (b) shows the change in the peak values of the line voltages with phase transposition is 3.5132 keeping machine 3 phase shift constant. Fig. 8.9(c) shows the plot of peak of line voltages (p.u.) and phase shift angle (deg.) keeping machine 2 phase shift constant and Fig. 8.9(d) shows the plot keeping machine 1 phase shift constant. The ratio of these three values is 0.9011 indicating that instead of the dc link voltage of 3 p.u. the value of 2.7032 p.u. would have been sufficient.

Fig. 8.9 Plot of peak of line voltages (p.u.) and phase shift angle (deg.)

Fig. 8.9 (a) shows the plot of peak of line voltage with respect to the phase shift angle without increasing the modulation index and shows that the maximum value is 2.4837
p.u. rms (3.5126 peak p.u.), this will remain same in all the conditions. Fig. 8.9(b) shows the plot keeping machine 3 phase shift constant the plot of machine 1 & 2 with increased modulation index. Fig 8.9(c) shows the plot keeping machine 2 phase shift constant and Fig. 8.9 (d) shows the plot keeping machine 3 phase shift constant. In all the above conditions the value of the maximum peak is 2.7569 rms p.u. (3.8989 peak p.u.). The ratio between these two values is 0.9009 and the bus voltage required is 0.9009x3 = 2.7027V p.u. instead of 3 V p.u. This is a gain of 9.91% in DC bus value.

8.3.3 TIME EQUIVALENT SPACE VECTOR PULSE WIDTH MODULATION SCHEME (TESVPWM)

In the proposed algorithm the reference voltages are sampled at fixed time interval equal to the switching time. The sampled amplitudes are converted to equivalent time signals. The time signals thus obtained are imaginary quantities as they will be negative for negative reference voltage amplitudes. Thus a time offset is added to these signals to obtain the gating time of each inverter leg. This offset addition centres the active switching vectors within the switching interval offering high performance PWM similar to SVPWM. The algorithm is given below, Where \( V_x; \ x=a,b,c,d,e,f,g \) is the sampled amplitudes of reference phase voltages during sampling interval and \( T_s \) is the inverter switching period. \( T_x; \ x=a,b,c,d,e,f,g; \) are referred as time equivalents of the sampled amplitudes of reference phase voltages. \( T_{max} \) and \( T_{min} \) are the maximum and minimum values of \( T_x \) during sampling interval. \( T_o \) is the time duration for which the zero vectors is applied in the switching interval. \( T_{offset} \) is the offset time when added to time equivalent becomes gating time signal or the inverter leg switching time \( T_{gx}; \ x=a,b,c,d,e,f,g \).

**Algorithm of the proposed TESVPWM:**
1. Sample the reference voltages \( V_a, V_b, V_c, V_d, V_e, V_f, \) and \( V_g \) in every switching period \( T_s \).
2. Determine the equivalent times \( T_1, T_2, T_3, T_4, T_5, T_6 \) & \( T_7 \) given by expression, where \( x \)
   \[
   T_x = V_x \times \frac{T_s}{V_{dc}}; \quad a,b,c,d,e,f, \text{and} \ g
   \]
3. Determine \( T_{offset} \):
   \[
   T_{offset} = \frac{T_s}{2} - \frac{T_{max} + T_{min}}{V_{dc}}
   \]
4. Then the inverter leg switching times are obtained as
   \[
   T_{gx} = T_x + T_{offset}, \quad x = a,b,c,d,e,f, \text{and} \ g
   \]
Fig. 8.10 shows the principle of Time Equivalent method for seven-phase series connected drives, if one fundamental cycle of modulating signal is divided into ten equal parts (sectors) and sampling is done in the first part then the equivalent mathematical analysis for first part is given below and on the basis of this analysis the equivalent switching waveform is shown in Fig. 8.11.

For Sector 1

\[ T_{\max} = T_a; T_{\min} = T_c; \]  
\[ T_1 = T_a - T_h; T_2 = T_b - T_d; T_3 = T_c - T_e; T_4 = T_f - T_g; T_5 = T_g - T_f; T_0 = T_c - T_e; \]

\[ T_{\text{effective}} = T_{\max} - T_{\min} = T_a - T_c; \]

\[ T_0 = T_c - T_{\text{effective}}; \]

\[ T_{\text{offset}} = \frac{T_0}{2} - T_{\min} = \frac{T_0}{2} - T_c; \]

\[ T_{\text{g}a} = T_a + T_{\text{offset}} = T_a + \frac{T_0}{2} - T_{\min} = T_a + \frac{T_0}{2} - T_c = \frac{T_0}{2} + T_1 + T_2 + T_3 + T_4 + T_5 + T_6; \]

\[ T_{\text{gb}} = T_b + T_{\text{offset}} = T_b + \frac{T_0}{2} - T_{\min} = T_b + \frac{T_0}{2} - T_c = \frac{T_0}{2} + T_2 + T_3 + T_4 + T_5 + T_6; \]

\[ T_{\text{gc}} = T_c + T_{\text{offset}} = T_c + \frac{T_0}{2} - T_{\min} = T_c + \frac{T_0}{2}; \]

\[ T_{\text{gd}} = T_d + T_{\text{offset}} = T_d + \frac{T_0}{2} - T_{\min} = T_d + \frac{T_0}{2} + T_3 + T_4 + T_5 + T_6; \]

\[ T_{\text{ge}} = T_e + T_{\text{offset}} = T_e + \frac{T_0}{2} - T_{\min} = T_e + \frac{T_0}{2} + T_4 + T_5 + T_6; \]

\[ T_{\text{gf}} = T_f + T_{\text{offset}} = T_f + \frac{T_0}{2} - T_{\min} = T_f + \frac{T_0}{2} + T_5 + T_6; \]

\[ T_{\text{gg}} = T_g + T_{\text{offset}} = T_g + \frac{T_0}{2} - T_{\min} = T_g + \frac{T_0}{2} + T_6; \]
Fig. 8.10 Principal of TESVPWM for sector I
Fig. 8.11 switching waveforms for sector 1 using the proposed TESVPWM

(a) Harmonic spectrum of phase ‘a’ voltage

(b) Filtered output voltage

(c) Inverter Alpha axis phase ‘a’ voltage spectrum

(d) Inverter xi-yl axis phase ‘a’ voltage spectrum
Simulation results are provided in Fig. 8.12. The harmonic analysis of output voltage phase ‘a’ is carried out and the resulting time domain and frequency domain waveform is illustrated in Fig. 8.12(a). It is clearly seen from the spectrum that the inverter output phase voltage contain only three desired frequency component fulfilling the criteria of independent control of Seven-phase series-connected three-motor drive system. The filtered output currents are shown in Fig. 8.12(b). The harmonic spectrum for the phase ‘a’ in $\alpha-\beta$ axis is shown in Fig. 8.12(c). Fig. 8.12(d) shows the harmonic spectrum in $x_1-y_1$ axis and Fig. 8.12(e) shows the harmonic spectrum in $x_2-y_2$ axis. The equivalent time signals are calculated according to the proposed algorithm and then the actual gating time is obtained by adding offset to the equivalent time signals and the resulting waveforms are shown in...
Fig. 8.12(g) shows the equivalent gating signals (or modulating signals) for all the Seven
phases and Fig. 8.18(h) represents the offset time $T_{\text{offset}}$. The offset time is the middle
portion of the $T_{\text{offset,max}}$ and $T_{\text{offset,min}}$, where $T_{\text{offset,max}} = T_s - T_{\text{max}}$ and $T_{\text{offset,min}} = -T_{\text{min}}$

From the switching waveform of Fig. 8.11, for first part the space vectors used are
64, 96, 104, 108, 110 and 111 for the implementation of modulation scheme. Their positions
in the $d$-$q$ plane can be seen in Fig. 7.2, in $x_1$-$y_1$ plane in Fig. 7.3 and in $x_2$-$y_2$ plane in Fig. 7.4.

### 8.3.4 ARTIFICIAL NEURAL NETWORK BASED SPACE VECTOR PULSE WIDTH
MODULATION

![Functional Block diagram of ANN based SVM](image)

**Fig. 8.13 Functional Block diagram of ANN based SVM for a seven-phase VSI**

![Matlab/Simulink model for the ANN based SVM scheme for Seven-phase VSI](image)

**Fig. 8.14 Matlab/Simulink model for the ANN based SVM scheme for Seven-phase VSI supplying Seven-phase series connected three motor drive system**
The ANN based space vector PWM technique for a Seven-phase isolated neutral load of a voltage fed inverter is already discussed in chapter 7. This section describes the ANN PWM based on TESVPWM scheme. The reference signal in TESVPWM is taken as input neuron values and the modulating signals in TESVPWM scheme is taken as the target values. The functional block diagram and Matlab/Simulink model for the Seven-phase VSI supplying Seven-phase series connected three motor drive system are shown in Fig. 8.13 and Fig. 8.14. Then the Matlab neural network tool is used for the training and simulation purpose which is later formed the ANN block for the above scheme. Input and output layer with seven neuron and hidden layer with ten neurons. Network is Feed-forward back propagation type and the training function “trainlm” is used for the simulation purpose. The adaptation learning function is LEARNGDM and Mean squared error (MSE) performance function is used. Transfer function is TANSIG (tansigmoidal) type. The simulation results for voltage source inverter are shown in Fig. 8.15.
Fig. 8.15 shows the simulation results of the ANN based space vector PWM scheme. Fig. 8.15(a) shows the harmonic spectrum for the phase 'a' voltage and the filtered output currents are shown in Fig. 8.15(b). The harmonic spectrum for the phase 'a' voltage in alpha axis is shown in Fig. 8.15(c) and in $x_1y_1$ axis is shown in Fig. 8.15(d). The harmonic spectrum for the phase 'a' voltage in $x_2y_2$ axis is shown in Fig. 8.15(e) and Fig. 8.15(f) shows the equivalent modulating signals.

Thus it can be concluded that the ANN based PWM offers similar performance as that of TESVPWM method.