Respected Sir,

Thanks for providing valuable review comments. Please find herewith corrections and justification against review comments for the paper titled “ANN based Over-modulated Space Vector Pulse Width Modulator For VCIM Drives”. You are kindly requested to recommend the paper for journal publication.

**Comment-(1):** “to reconsider the claim of lower current distortion as it is not apparent from the figures unless the TDH is given”.

**Justification/Correction:** Table-I is added in the paper which shows the comparison of TDH in phase voltage and phase current for conventional method and proposed overmodulation method.

**Comment-(2):** “it seems to us that the main merit of the paper is its apriori-given ANN weighting factors, thus reducing the on line computing effort “.

**Justification/Correction:** Reducing the on line computing effort is in fact is one of the merits of the method, but by Synthesizing and Designing the reference voltage $V_{\text{ref}}$ (refer equation (19) and (20)) with less harmful harmonics content may further reduces the TDH in the current and voltage which will further reduces the losses. This will makes more suitable to use the method in overmodulation mode-I and mode-II operation. (The above justification is already claimed in conclusion section)

**Comment-(3):** “the motor plus converter losses comparisons, in overmodulation mode, with the proposed and conventional PWM are needed”.

**Justification/Correction:** As it is seen from the Table-I, that the proposed method is having less TDH compare to the conventional method. The harmonic current in proposed method is less than the conventional method which will reduce harmonic torque and other losses in drive. Switching frequency is selected such that it should produce minimal switching loss and harmonics loss.

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ANN BASED OVER-MODULATED SPACE VECTOR PULSE WIDTH MODULATOR FOR VCIM DRIVES

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Abstract: A high performance overmodulation strategy for PWM voltage-source inverter (VSI) fed induction motor drive is proposed in this paper. Kohonen’s Competitive Net based space vector PWM is used to extend its operation from under-modulation (linear mode) to over-modulation (non-linear mode) that is smoothly up to six-step mode. This ANN-based modulator was then incorporated in induction motor drive with rotor flux oriented vector control. This scheme is evaluated under simulation for a variety of operating conditions of the drive. As the full inverter voltage utilization is important from cost and power density improvement perspective, the scheme presents the robust and best strategy for drives operation extended up to six-step mode.

Key words: Space Vector Pulse Width Modulation (SVPWM), Modulation Index, Vector Controlled Induction Motor (VCIM), Kohonen’s Competitive Net.

1. Introduction

The carrier-based pulse width modulation (PWM) methods are the preferred approach in most drive applications due to the low harmonic spectrum, the fixed switching frequency and the implementation simplicity. Carrier-based PWM operation can be divided into two modes [1]:

- Linear Mode: In this mode of operation, the peak of a modulation signal is less than or equal to the peak of the carrier signal. When the carrier frequency is greater than twenty times modulation signal frequency, the gain of PWM is nearly equal to 1 (G ≈ 1).
- Nonlinear Mode: In this mode of operation, the peak of a modulation signal is greater than the peak of the carrier signal, over-modulation occurs with G<1. The six-step mode makes the end of the nonlinear mode.

Carrier-based PWM is further classified [2] into suboscillation method and space vector pulse width modulation (SVPWM). In suboscillation method the maximum value of the modulation index (m) is 0.785 reached at a point where the amplitudes of the reference and the carrier signal become equal. In SVPWM the maximum modulation index extends up to 0.907.

Drive operation in the nonlinear modulation range i.e. in over-modulation range had following problems [3]: 1) large amounts of sub-carrier frequency harmonic currents are generated; 2) the fundamental component voltage gain significantly decreases and 3) the switching device gate pulses are abruptly dropped.

In current-controlled drives [4]-[7], overmodulation operation results into sub-carrier frequency harmonic distortion and current regulator performance reduction. The current regulators are heavily burdened by the feedback current sub-carrier frequency harmonics, regulator saturation and oscillatory operations. On the other hand, full inverter voltage utilization is important from cost and power density improvement perspective. Also a drive with high performance over-modulation range operating capability is less sensitive to inverter dc-bus voltage sag and hence increases drive reliability. Recently over-modulation issues have attracted the attention of many researchers. Neural network based over-modulation implementation has many advantages such as gives higher switching frequency, lesser harmonics and robust control [8]-[12]. Section–II presents the behavior of field oriented control under overmodulation. Section–III and IV present conventional and neural network based SVPWM in voltage source inverter respectively. The proposed ANN-based overmodulation strategy is presented in section–V, for the SVPWM voltage-source inverter and was incorporated in rotor flux oriented vector control induction motor drive.

2. Field Oriented Control

The field oriented induction machine model, shows the decoupled system that results when current coincidence exists (necessary condition) and the slip is selected to maintain the q-axis rotor flux at zero (sufficient condition). To achieve current coincidence, a current regulator is often employed. Early attempts at current regulation were simple implementations of a stationary frame PI regulator. The stationary PI is recognized to have nonzero steady state error, but the high gain of the stationary compensator and inverter reduces the phase lag between the command and feedback current while in the linear region.

However, the unique characteristics of the stationary PI make it inherently unsuited for Field oriented control (FOC) regardless of the additional compensation techniques employed [6]. The controller was transformed to the synchronous frame wherein all quantities are dc as in Fig. 1. Independent control of each component of current, flux producing current
The inability to apply the correct voltage vector-phase and magnitude to ensure current coincidence degrades the quality of the FOC; in the extreme case, it invalidates the necessary and sufficient conditions for field orientation.

The objective of overmodulation algorithm is to compensate the modulating wave in phase and magnitude to account for bus variation and the reduced gain while maintaining a unity transfer function. The scheme for vector control induction motor drive with neural network based space vector modulated VSI is shown in Fig. 2.

3. Conventional SVPWM in voltage source inverter

In voltage source inverter [1]-[3], depending on the switching states, the space vector of the stator phase voltages can be in six different positions and there are two zero vectors, corresponding to the cases when the three inverter terminals are connected either to the positive or to the negative rail of the d.c. supply. The six non-zero voltage space vectors form a hexagonal locus. The zero space vectors are located at the origin of the reference frame. Any desired stator voltage space vector inside the hexagon can be obtained from the weighted combination of the eight switching vectors. It is the goal of the space vector modulation technique to reproduce the reference stator voltage space vector by using the appropriate switching vector, under the constraint of minimal harmonic current distortion and with shortest possible cycle time.

In order to reduce the number of switching actions and to make full use of active turn on time for space vectors, the vector $\overline{V}_{\text{ref}}$ is split into the two nearest
adjacent voltage vectors and zero vectors \( \overline{V_0} \) and \( \overline{V_T} \) in an arbitrary sector. For Sector 1 in one sampling interval, vector \( \overline{V_{\text{ref}}} \) can be given as

\[
\overline{V_{\text{ref}}} = V_1 T_1 + V_2 T_2 + V_3 T_3 + V_4 T_4 + V_5 T_5 + V_0 T_6
\]  

(2)

where \( T_1 \), \( T_2 \), \( T_3 \), \( T_4 \), \( T_5 \), \( T_6 \) are respectively the on duration of the adjacent switching state vectors \( \{V_1, V_2, V_3, V_4, V_5, V_0\} \) that are called active vectors and \( \overline{V_0}, \overline{V_T} \) are called zero vectors. In general

\[
\overline{V_{\text{ref}}} T_S = V_1 T_1 + V_{i+1} T_{i+1} + V_7 T_7 + V_T 0 T_0
\]  

(3)

where \( T_1, T_2, T_3, T_6, T_0, T_7 \) are respectively on duration of the adjacent switching state vectors \( \{V_1, V_2, V_3, V_4, V_5, V_0\} \). The on durations are defined as follows:

\[
T_1 = m T_S \sin(60 - \theta)
\]  

(4)

\[
T_{i+1} = m T_S \sin(\theta)
\]  

(5)

\[
T_2 + T_0 = T_S - T_1 - T_{i+1}
\]  

(6)

where \( m \) is modulation index defined as:

\[
m = \frac{2}{3} \sqrt{\frac{V_{\text{ref}}}{V_{\text{dc}}}}
\]  

(7)

\( V_{\text{dc}} \) is d.c. bus voltage and \( \theta \) is angle between the reference voltage \( \overline{V_{\text{ref}}} \) and the closest clockwise state vector as depicted in Fig. 3.

It is also possible to use an ANN based on Kohonen’s competitive layers. In this paper modified Kohonen’s competitive layers is proposed. It has two winner neurons and the outputs of the winner neurons are set to their net inputs. If normalized values of the input vectors are used, then the six outputs (six net values \( n_1, n_2, \ldots, n_6 \)) will be proportional to the cosine of the angle between the reference voltage vector and one of the six switching vectors. The two largest net values are then selected. These are \( n_i \) and \( n_{i+1} \), proportional to \( \cos(\theta) \) and \( \cos(60 - \theta) \). Since the space vector modulation is a deterministic problem and all classes are known in advance, there is no need to train the competitive layer.

\[
\text{net} = \overline{V_{\text{ref}}} T_S = \left| \overline{V_{\text{ref}}} \right| | \cos(\theta) |
\]  

(8)

Since the input vector and the weight vector are normalized, the instars net input gives the cosine of the angles between the input vector and the weight vectors that represent the classes. The largest instar net input wins the competition and the input vector is then classified in that class. The winner of the competition is the closest vector to the reference vector. The six net values can be written in a matrix form for all neurons as:

\[
\begin{bmatrix}
 n_1 \\
 n_2 \\
 n_3 \\
 n_4 \\
 n_5 \\
 n_6 \\
\end{bmatrix} =
\begin{bmatrix}
 1 & -1/2 & -1/2 \\
 1/2 & 1/2 & -1 \\
 -1/2 & 1 & -1/2 \\
 -1 & 1/2 & 1/2 \\
 -1/2 & -1/2 & 1 \\
 1/2 & -1 & 1/2 \\
\end{bmatrix}
\begin{bmatrix}
 \overline{V_{\text{ref}}} \\
 \overline{V_{\text{ref}}} \\
 \overline{V_{\text{ref}}} \\
 \overline{V_{\text{ref}}} \\
 \overline{V_{\text{ref}}} \\
 \overline{V_{\text{ref}}} \\
\end{bmatrix}
\]  

(9)
where
\[
\begin{bmatrix}
1 & 1/2 & -1/2 & -1 & -1/2 & 1/2 \\
-1/2 & 1/2 & 1 & -1/2 & -1 & 1/2 \\
-1/2 & -1 & 1/2 & -1 & 1/2 & 1/2
\end{bmatrix}
\begin{bmatrix}
T_1 \\
W
\end{bmatrix}
\begin{bmatrix}
V_{\text{Aref}} \\
V_{\text{Bref}} \\
V_{\text{Cref}}
\end{bmatrix}
\]

Assuming \( V_{\text{Aref}} \) is applied to the competitive layer and \( n_i \) and \( n_{i+1} \) are the neurons who win the competition. Then from equation (8) we have
\[
\begin{bmatrix}
\eta_i \\
\eta_{i+1}
\end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix}
\cos(\theta) \\
\cos(60 - \theta)
\end{bmatrix} \begin{bmatrix}
\eta_i \\
\eta_{i+1}
\end{bmatrix}
\]

Also
\[
\begin{bmatrix}
\cos(\theta) \\
\cos(60 - \theta)
\end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix}
1/2 \\
1/2
\end{bmatrix}
\begin{bmatrix}
\sin(60 - \theta) \\
\sin(\theta)
\end{bmatrix} \begin{bmatrix}
\eta_i \\
\eta_{i+1}
\end{bmatrix}
\]

Using equation (10) and equation (11) we get
\[
\begin{bmatrix}
T_i \\
T_{i+1}
\end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix}
1 \\
1
\end{bmatrix} \begin{bmatrix}
\sin(60 - \theta) \\
\sin(\theta)
\end{bmatrix} \begin{bmatrix}
\eta_i \\
\eta_{i+1}
\end{bmatrix}
\]

Equation (12) is the on duration of the consecutive adjacent switching state vector \( V_i \) and \( V_{i+1} \), which is same as equation (4) and equation (5). Therefore we have
\[
\begin{bmatrix}
T_i \\
T_{i+1}
\end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix}
1 \\
1
\end{bmatrix} \begin{bmatrix}
\sin(60 - \theta) \\
\sin(\theta)
\end{bmatrix} \begin{bmatrix}
\eta_i \\
\eta_{i+1}
\end{bmatrix}
\]

The implementation of this method is depicted in Fig. 4. first \( n_k \) for \( k=1 \ldots \ldots \theta \) are calculated. Two largest \( \eta_i, \eta_{i+1} \) and their corresponding indexes (i.e. \( i \) and \( i+1 \)) are selected by Kohonen’s competitive network. The on duration (\( T_i \) and \( T_{i+1} \)) of the two adjacent space vectors are computed. The space vector \( V_i \) and \( V_{i+1} \) are selected according to the value of \( i \) and \( i+1 \). When adjacent vectors and on times are determined the procedure for defining the sequence for implementing the chosen combination is identical to that used in conventional space vector modulation.

5. Overmodulation Implementation In SVPWM
As the modulation index increases, the radius of the circular trajectory in the linear region increases until at \( m = 1 \), it becomes the circle inscribed by the hexagon. For this value of modulation index, the on duration of the zero vector reduces to zero, when the reference vector touches the hexagon at \( \theta = (2k + 1)\pi/6 \) where \( k = 0,1, - - - 5 \). This is the upper limit of the linear modulation [9]-[12]. Further increase in modulation index while keeping a circular voltage vector to smoothly deviate from a sinusoidal circular trajectory reaching ultimately a discrete six-step switching sequence. For continuous control over the modulation index, the transition from the sinusoidal modulation to six-step operation is divided into two modes, namely mode I and mode II. The maximum output voltage in mode I and mode II are obtained at \( m_2 = 1.052 \) and \( m_3 = 1.13 \) respectively. Based on the modulation index, the selector chooses among linear modulation, overmodulation mode I and overmodulation mode II.

A. Overmodulation Mode I
In overmodulation Mode I, the reference vector is distorted at a specific angle and the distorted vector \( V_{\text{Aref}} \) is allowed to move along the hexagon side until the requested modulation index is obtained. The on duration of the zero vector is zero, as long as the end of this vector remains on the hexagon side. The maximum attainable modulation index in this mode of operation \( m_2 \) is reached when the distorted reference vector remains on the hexagon side for all \( \theta \).

Here
\[
T_i + T_{i+1} = T_k
\]

Putting \( T_i \) and \( T_{i+1} \) above from (3) and (4) gives
\[
m = \frac{1}{\sin(\theta) + \sin(60 - \theta)}
\]

For this \( m \), the on durations of the adjacent active switching vector are given by

![Fig. 4. Modified Kohonen’s competitive layer based implementation of the space vector modulation technique for VSI.](image-url)
\[
\sin(60-\theta) \cdot \text{msin}(60-\theta) T = \text{T}_{\text{is}} = \text{T}_{\text{s}} \cdot \sin \theta + \text{msin}(60-\theta) + \text{msin}(60-\theta) \tag{16}
\]

\[
T = T_{i} + T_{i+1} \tag{17}
\]

If \(\alpha_t\) is the voltage reference angle at which the transition from circular sinusoidal trajectory to the hexagon takes place, the average modulation index over \(AB\) in Fig. 5. therefore can be calculated from

\[
m = \frac{2}{\sin(60-\theta)} \int_{\alpha_t}^{\pi/2} \frac{\Pi_4}{\cos(\Pi/4-\alpha)} \, d\alpha \tag{18}
\]

which gives

\[
m = \frac{1}{2} \ln \left( \frac{\sin(\Pi/6-\alpha)}{\sin(\Pi/6-\alpha_t)} \right) \tag{19}
\]

Since at \(\theta = 30^\circ\), \(\text{msin}\theta\) and \(\text{msin}(60-\theta)\) are equal, the modulation index can easily be obtained from the addition of these two at \(\theta = 30^\circ\). For all other angles, \(m\) remains unchanged. Using this technique, the instantaneous modulation index will be modified six times during one period of the reference voltage. In this mode \(m\) as a function of \(\text{msin}_{\alpha_t}\) is calculated and stored in the form of a lookup table. For a given value of \(m\), the corresponding \(\text{msin}_{\alpha_t}\) can be reasonably approximated. A decision then is made based upon a comparison between the calculated \(\text{msin}_{\alpha_t}\) and the \(\text{msin}\theta\) output of the network of Fig. 2. The on duration of the corresponding switching vectors then are calculated either from (3)-(5), for end of reference vector on circular trajectory or from (16)-(17), for end of reference vector on the hexagon side.

**B. Overmodulation Mode II**

In overmodulation Mode II, the modulation index further increases from \(m_2 = 1.05\) to \(m_3 = 1.1\) of the six-step maximum.

The reference voltage vector \(\overline{V}_{\text{ref}}\) is distorted in both magnitude and phase angle. The trajectory of the distorted reference vector jumps from a discrete six-step switching to a continuous hexagon side at a specific angle \(\alpha_h\). Such a switching method is identified by a hold angle \(\alpha_h\), which controls the time the distorted reference remains at the vertices. From the fundamental component of the distorted voltage as shown in Fig. 6., the modulation index as a function of \(\alpha_h\) is given by

\[
m = \frac{\sqrt{3}}{\Pi} \left( 2\alpha_h \cos(\Pi/6 - \alpha_h) + 2\text{sin}(\Pi/6 - \alpha_h) + a_h \cos(\Pi/6 - \alpha_h) + a_h \sin(\Pi/6 - \alpha_h) + a_h \text{sin}(\Pi/6 - \alpha_h) + a_h \cos(\Pi/6 - \alpha_h) \right) \tag{20}
\]

In this mode, \(m\) as a function of \(\text{msin}_{\alpha_h}\) is calculated and stored in the form of a lookup table. For a given value of \(m\), the corresponding \(\text{msin}_{\alpha_h}\) can be reasonably approximated. A decision then can be made based upon a comparison between the calculated and the current \(\text{msin}\theta\) from the network in Fig. 2. and appropriate switching vectors are switched accordingly. Fig. 7. presents the proposed strategy for continuous operation from linear modulation to overmodulation for SVPWM inverter.
6. Simulation Results with Overmodulated SVPWM

In SVPWM switching harmonics are suppressed to a large extent by the low-pass characteristic of the machine inductances and by the inertia of the mechanical system. The remaining distortions of the current waveforms and the electromagnetic torque can be valued by performance criteria. Although the torque harmonics are produced by the harmonic currents, there is no stringent relationship between both of them. Lower torque ripple can go along with higher current harmonics and vice versa. The simulation results of ANN-based overmodulation strategy are presented in Fig. 8. to Fig.13. for the SVPWM voltage-source inverter based rotor flux oriented vector control induction motor drive. Fig. 8. and Fig. 9. shows phase voltages and their spectra in the overmodulation region with ANN based proposed method and conventional method respectively. Fig. 10. and Fig.11. shows phase currents and their spectra in the overmodulation region with ANN based proposed method and conventional method respectively. The switching frequency was at 3 kHz and with constant load of 8 Nm. Table-I present the comparison of TDH in both the methods at different modulation index. The data shows less TDH for proposed method and hence less losses. Fig. 12. shows the phase current transition from six-step to PWM mode when modulation index decreases form 1.1 to 0.8. Fig. 13. shows time responses of speed, current, torque and duty-cycle for vector control induction motor drive with dynamic

Fig. 7. Linear modulation to overmodulation strategy for SVPWM inverter

Fig. 8. Phase Voltages and their spectra in the overmodulation region with proposed method for various modulation index.

Fig. 9. Phase Voltages and their spectra in the overmodulation region with conventional method for various modulation index.

Fig. 10. Phase Voltages and their spectra in the overmodulation region with proposed method for various modulation index.

Fig. 11. Phase Voltages and their spectra in the overmodulation region with conventional method for various modulation index.
overmodulation behavior (for m=1.1) under speed reversal and at constant load torque. The results show better overall performance of ANN based overmodulation strategy for vector control induction motor drive.

**Fig. 10.** Phase currents and their spectra in the overmodulation region with proposed scheme for various modulation index.

**Fig. 11.** Phase currents and their spectra in the overmodulation region with conventional method for various modulation index.

**TABLE I**

<table>
<thead>
<tr>
<th>Modulation Index (m)</th>
<th>Conventional Method TDH (in % of fundamental)</th>
<th>Overmodulation Method TDH (in % of fundamental)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.23</td>
<td>8.81</td>
</tr>
<tr>
<td>1.05</td>
<td>6.99</td>
<td>6.18</td>
</tr>
<tr>
<td>1.1</td>
<td>6.82</td>
<td>6.44</td>
</tr>
</tbody>
</table>

**Phase voltage TDH**

**Phase current TDH**

**Fig. 12.** Transition from six-step to PWM mode.

**Fig. 13.** Vector control induction motor drive with dynamic overmodulation behavior (for m=1.1) under speed reversal and constant load torque.
7. Conclusion

ANN based SVPWM has been described, that operates very well in undermodulation as well as in overmodulation including mode-I and mode-II regions. The scheme is evaluated with rotor flux oriented vector controlled induction motor drive. The ANN based SVPWM can give higher switching frequency, which is not possible with conventional DSP based SVPWM. Also the distortion of the reference vector in the overmodulation region is reduced, resulting in reduced output distortion and less losses in the drive. The drive performance was best under dynamic operation.

Appendix

The parameters of induction motor are as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>2.2KW</td>
</tr>
<tr>
<td>r_s</td>
<td>1.77 ohms</td>
</tr>
<tr>
<td>r_r</td>
<td>1.34 ohms</td>
</tr>
<tr>
<td>X_l</td>
<td>5.25 ohms</td>
</tr>
<tr>
<td>X_l</td>
<td>4.57 ohms</td>
</tr>
<tr>
<td>X_m</td>
<td>139 ohms</td>
</tr>
<tr>
<td>J</td>
<td>0.025 Kg.m²</td>
</tr>
<tr>
<td>p</td>
<td>4</td>
</tr>
</tbody>
</table>

References


