A Novel Solution for Sensing 3φ Current of VSI Based Ac Drives Using Single Current Sensor

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ABSTRACT: In this thesis a technique for measuring and controlling line currents of three phase AC motors using information from a single current sensor resistor mounted in the DC-link of an inverter is presented. The principal motivation is to reduce the sensor cost, weight, and volume and also to improve the reliability of a drive system. However the basic dc link single current sensor technique poses a limitation because the duration of the active voltage vectors must be long enough to measure the dc link current reliably. To overcome this problem a new algorithm called the measurement vector insertion method is presented along with basic single current sensor technique that overcomes this problem using active voltage vectors that are applied for brief measurement intervals only when needed during each cycle of fundamental frequency.

Key Words: AC drive, three phase PWM inverter, phase current regulation, single current sensor, vectors control.

I. INTRODUCTION

Three phase pulse width modulation voltage fed inverters are recently showing growing popularity for multi-megawatt industrial drive applications. Such as such as variable-speed ac motor drives and uninterruptible power supplies (UPS) for such applications knowledge of phase current is an essential requirement. Generally currents are measured using two or three current sensors which are mounted in the inverter output leads connected to the three-phase load. The alternate approach of measuring these phase currents by using a single current sensor which is mounted in the DC link of the inverter to measure the phase current sequentially measuring three phase current of three phase drives using a single current sensors is called as single current sensor technique (SCST). The main advantage of this technique is to reduce current sensor cost, weight, and volume requirements. In addition, the use of a single dc link current sensor eliminates undesirable unbalances in the phase currents and pulsating torque caused by mismatches of current sensor sensitivities. In PWM operation of voltage-fed three-phase inverters, all the three phase currents appears in the dc-link current one by one at every switching instant whenever an active (i.e., non-zero) voltage vector is applied to the load.

Thus, measuring the dc link current makes it possible to measure the phase currents sequentially as the inverter switching states change. However, if the duration of active switching state is not long enough, DC current cannot measure reliably. The minimum time required for reliable dc link current measurement is

$$T_{\text{min}} = t_d + t_{\text{rr}} + t_{\text{AD}}$$

Where

- $t_d =$ inverter dead time,
- $t_{\text{rr}} =$ diode reverse-recovery time,
- $t_{\text{AD}} =$ sensor A/D acquisition

The later part of this paper explains measurement vector theory which shows the space vector diagram in which unmeasurable areas (cross-hatched) in the inverter output voltage space vector plane is shown for which at least one of the PWM duty cycle intervals is too short to measure the phase currents available in the dc link current. If the reference voltage vector falls into such an unmeasurable area, the three phase currents will not be reliably detected since one or more of the active state vectors are not applied long enough to insure accurate measurements. A high-quality phase current reconstruction and regulation using a dc link current sensor can be achieving by a new single current sensing algorithm which is proposed in this paper.
This algorithm introduces a special switching sequence whenever the reference voltage vector falls into one of the unmeasurable regions to insure that all three phase currents are measurable. In the first switching interval, the PWM algorithm generates a reference voltage vector according to basic SVPWM operation. During the second switching interval, the new method introduces three special measurement vectors so that all three phase currents can be sequentially measured during this interval.

II. THREE PHASE PWM VSI DRIVES AND SVPWM

A. PWM of VSI

Output voltage from an inverter can also be adjusted by exercising a control within the inverter itself. The most efficient method of doing this is by pulse-width modulation control used within an inverter. In this method, a fixed dc input voltage is given to the inverter and a controlled ac output voltage is obtained by adjusting the on and off periods of the inverter components.

B. Space Vector PWM

Sinusoidal PWM has been a very popular technique used in AC motor control. However, this method is unable to make full use of the inverter’s supply voltage and the asymmetrical nature of the PWM switching characteristics produces relatively high harmonic distortion in the supply. Space Vector PWM (SVPWM) is a more sophisticated technique for generating a fundamental sine wave that provides a higher voltage to the motor and lower total harmonic distortion, it is also compatible for use in vector control of AC motors.

Due to its compatibility for use in vector control of AC motors, Space Vector Modulation (SVPWM) is one of the most widely utilized techniques to generate sinusoidal line-to-line voltages and currents with a three-phase inverter.

\[ \begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \frac{1}{3} V_{dc} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \]

Fig. 1. Three phase voltage source inverter.

(1) Space Vector PWM Technique: The structure of a typical three-phase voltage source power inverter is shown in Figure 1. \( V_a, V_b, \) and \( V_c \) are the output voltages applied to the windings of a motor. Q1 through Q6 are the six power transistors that shape the output, which are controlled by \( a, a', b, b', c, \) and \( c' \). For AC Induction motor control, when an upper transistor is switched on, i.e., when \( a, b \) or \( c \) is 1, the corresponding lower transistor is switched off, i.e., the corresponding \( a', b' \) or \( c' \) is 0.

The relationship between the switching variable vector \( [a, b, c] \) and the line to line voltage vector \( [V_{ab}, V_{bc}, V_{ca}] \) is given by (1) in the following:

\[
\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \frac{1}{3} V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}
\]
Table 1 below shows all the switching states of three phase voltage source inverter. Number of conducting thyristor in each state is also listed in table. Assuming d and q are the horizontal and vertical axes of the stator coordinate frame, then the d-q transformation given is equation (3) can transformation three phase voltage vector into a vector in the d-q coordinate frame which represents the special vector sum of the three phase voltage.

Switching States of Three Phase combinations of switching patterns can be mapped into the d-q plane in figure 2 by the same d-q transformation.

Table 1.

<table>
<thead>
<tr>
<th>State</th>
<th>Conducting Transistor</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>T2, T4, T6</td>
</tr>
<tr>
<td>001</td>
<td>T2, T4, T5</td>
</tr>
<tr>
<td>010</td>
<td>T2, T3, T6</td>
</tr>
<tr>
<td>011</td>
<td>T2, T3, T5</td>
</tr>
<tr>
<td>100</td>
<td>T1, T4, T6</td>
</tr>
<tr>
<td>101</td>
<td>T1, T4, T5</td>
</tr>
<tr>
<td>110</td>
<td>T1, T3, T6</td>
</tr>
<tr>
<td>111</td>
<td>T1, T3, T5</td>
</tr>
</tbody>
</table>

Fig. 2. The basic space vector and switching patterns.

Table 2.

<table>
<thead>
<tr>
<th>Voltage Vector</th>
<th>DC Link Current $I_{dc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1 = (100)</td>
<td>$+i_a$</td>
</tr>
<tr>
<td>V2 = (110)</td>
<td>$-i_b$</td>
</tr>
<tr>
<td>V3 = (010)</td>
<td>$+i_b$</td>
</tr>
<tr>
<td>V4 = (011)</td>
<td>$-i_a$</td>
</tr>
<tr>
<td>V5 = (001)</td>
<td>$+i_a$</td>
</tr>
<tr>
<td>V6 = (101)</td>
<td>$-i_b$</td>
</tr>
<tr>
<td>V7 = (111)</td>
<td>0</td>
</tr>
<tr>
<td>V8 = (000)</td>
<td>0</td>
</tr>
</tbody>
</table>
III. MEASUREMENT VECTORS INSERSION

In Fig. 4 the cross-hatched portion shows the area which is unmeasurable in the inverter output voltage space vector plane for which at least one of the PWM duty cycle intervals is too short to measure the phase currents available in the dc link current. If length of reference voltage vector is too short it will fall into such an unmeasurable area, and hence the three phase currents cannot be detected reliably since one or more of the active state vectors are not applied long enough to insure accurate measurements. These unmeasurable regions are centered around the six active voltage vectors for which the corresponding active voltage vector dominates the PWM interval, making it difficult to detect a second phase current before the switching cycle ends.

A. Measurement Vectors

For achieving high-quality and reliable phase current reconstruction using single current sensor. A method is proposed and simulated in this paper. The proposed method effectively overcomes the problem created by the unmeasurable intervals discussed above. The new concept introduces a special switching sequence whenever the reference voltage vector falls into one of the unmeasurable. This is shown in fig. 4 the first part of figure shows basic SVPWM operation, In the first switching interval Ts1 the PWM algorithm generates a reference voltage vector according to basic SVPWM operation. During the second switching interval Ts2. The new method introduces three special measurement vectors so that all three phase currents can be sequentially measured during this interval. This new concept is called as measurement vectors insertion method.
The above figure shows Example of PWM timing waveforms for basic MVIM algorithm for reference vector in vicinity of (100) active voltage vector with $T_{s1} = T_{s2}$. $T_{s1}$ associated with classical SVPWM plus an additional switching interval $T_{s2}$ consisting of three equal measurement intervals $T_m$.

As shown in figure 5 the sum of the three measurement vectors is zero, so the resulting reference voltage vector always remains Unchanged. A group of three active space vectors consisting of [100], [010], and [101] can be applied. This section will focus on the orientation of the resulting voltage vector, with discussion of the amplitude presented in the following section.

As a starting point, the reference voltage vector $V_s$ in sector 1 of basic SVPWM is defined as follows:

$$V_s = \frac{T_{s2}}{T_{s200}} V_0 + \frac{T_{s1}}{T_{s200}} V_1 + \frac{T_{s}}{T_{s200}} V_2 = \frac{T_{s2}}{T_{s200}} V_0 + \frac{T_{s1}}{T_{s200}} V_1 \quad \text{or} \quad \frac{T_{s}}{T_{s200}} V_2$$

Where $T_{s1} = T_s + T_1 + T_2 + T_3$ is the PWM switching period. In comparison the total switching period according to the MVIM algorithm consists of the original $T_{s1}$ associated with classical SVPWM plus an additional switching interval $T_{s2}$ consisting of three equal measurement intervals $T_m$. An illustration of the PWM timing waveforms for this total switching period is provided in fig 6.

![Fig. 5. Basic concept of measurement vectors.](image1)

![Fig. 6. PWM timing waveforms.](image2)
The new reference voltage vector with application of three measurement vectors is exactly identical with the reference voltage vector of basic SVPWM except that the in the denominator of each factor is replaced by
Consequently, the resulting voltage reference vector with the MVIM algorithm has the same orientation as the original reference vector and its amplitude is scaled by the ratio as indicated effect is illustrated in Fig. 7.

One advantage of the MV algorithm is that it can be easily incorporated into existing SVPWM algorithms so that minimum modifications of existing PWM algorithms are required. Another advantage is that basic single current sensor technique can measure two phase current only. And the third phase current is calculated as negative sum of the two measured currents. But MV method measures all the three phase current sequentially. One more advantage of incorporating measurement vectors in basic SVPWM single current sensor is that it improves predictability of the current sampling time instants. When the basic single dc link current sensor technique is used, the time instants for the current measurements during each PWM switching cycle can vary significantly depending on the reference voltage amplitude and angular position.

Such unpredictability can degrade the quality of the phase current reconstruction, particularly if any significant time is allowed to elapse between the two phase current measurements. Under these circumstances, the accuracy of the third derived phase current (e.g. \( i_v = -(i_u + i_w) \)) will particularly suffer.

The disadvantage of measurement vector algorithms is that it cannot provide simultaneous measurements of all three phase currents though it makes a definite contribution to the quality of the current reconstruction. A result of the combination of features described above, MVIM is very effective for providing complete phase current feedback in both the sector boundary and low modulation regions of Fig. 4.

IV. SIMULATION RESULTS & DISCUSSION ON RESULTS

Test on the proposed models of three phase voltage source inverter using single current sensor with measurement vector is carried out with different values of measurement vectors. And the results are tabulated below for Comparison.

A. Tabulated Results

<table>
<thead>
<tr>
<th>SR.NO</th>
<th>M-FACTOR</th>
<th>SVPWM With Measurement vector method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Different values of measurement factor</td>
<td>THD of 3 phase current With Single current sensor</td>
</tr>
<tr>
<td>1.</td>
<td>0.01</td>
<td>0.1802</td>
</tr>
<tr>
<td>2.</td>
<td>0.04</td>
<td>1.782</td>
</tr>
<tr>
<td>3.</td>
<td>0.05</td>
<td>0.2378</td>
</tr>
<tr>
<td>4.</td>
<td>0.1</td>
<td>0.2272</td>
</tr>
</tbody>
</table>
Table 4. Results of Simulation of SCST Without Measurement Vectors.

<table>
<thead>
<tr>
<th>SR.NO</th>
<th>Basic SVPWM Technique without using Measurement vectors</th>
<th>THD of current With SCST</th>
<th>THD of 3Ø Current measured at three output leads of inverter using 3 current sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>2.146</td>
<td>0.2327</td>
<td></td>
</tr>
</tbody>
</table>

B. Discussions on Results

In The above results the total harmonic distortion of three phase current are calculated and tabulated. First table shows the result of single current sensor Technique(SCST) with measurement vector insertion and second table shows the result of SCST without measurement vectors. As shown in table 4 the required or actual THD of three phase current is approximately 0.2327, which is measured directly from three phase output of VSI using three current sensors. But calculated THD using only SCST is 2.146. And irrespective of M factor it will remain always same because in this we have not use measurement vectors. It is now clear that the value THD Using single current sensor only is very high (2.146) from the actual value (0.2327).

This high THD is reduced to a great extent by using SCST along with measurement vectors this is our proposed model. Result of respected model is shown in table 3.

As we can observe from the table 3 and associated waveforms drawn below M factor till 0.004 is not correct as THD value very much differ from actual or required THD value 0.23. Though they result in less power loss.

Also Wave form of the current is inaccurate with 0.04 M Factor. The THD is 1.782 which is quite high.

When M Factor is kept 0.05. The THD with single Current sensor technique is 0.2378 which is approximated equal to the THD of the current measured direct from the 3Ø output of the inverter i.e. required THD.

If we further increase M Factor though the THD will remain nearly equal to 0.23 but power loss will also increase so we can conclude that 0.05 is the most suitable value of measurement factor.

C. Resulted Waveforms

![Waveform 1](image1.png)

**Fig. 8.** Three phase current waveform measured at output terminal of voltage source inverter.

![Waveform 2](image2.png)

**Fig. 9.** Three phase current measured at DC link of VSI using SCST but without measurement vectors.
D. Waveform Description

The resulted waveform shown above is discussed below. The first waveform shown above fig 8 is actual or required waveform of three phase current which is measured directly using three current sensors connected at output three output leads of the inverter. All the other waveform are measured using Single current sensor connected at DC side of the inverter.

As we can see from the Resulted waveforms that 3ø current waveforms obtain from single current sensor of basic SVPWM model is highly distorted and unbalanced. Fig 9.

So we have implemented measurement vector algorithm in Basic SVPWM model And resulted waveform with different value of measurement factor is shown fig (10 -11).

The above Waveform shows that with measurement factor less then 0.05 the waveform of phase current is distorted and not the same as shown in figure 8. Fig 11 shows waveform with measurement factor 0.05 which is lest distorted and same as required one. and all the three phase current with measurement factor above 0.05 are less distorted waveform of three phase current.

Hence it is concluded that:

Measurement factor $\geq 0.05$

Measurement factor should be equal to or greater then 0.05.
V. CONCLUSION

The MVI method along with SCST outlined in this thesis provides a new control strategy for recreating 3 currents of AC motors drives faded by VSI. SCST used reduces the number of current sensors and decrease the cost and improve the system reliability. And MVIM used solves the problem of basic SVPWM technique related with low modulation index region. Hence High performance current regulation over a wide range of operating conditions with a minimum of undesirable side effects can be achieved by combining the MVIM algorithm with a conventional SCST.

This is shown that the insertion of measurement vectors make it possible to reconstruct the phase current with minimum impact on machines performance. The simulation results carried on this system shows that on comparison with other dc link SCST, MVIM provides an appealing trade off between current waveform THD & inverter losses. So it is concluded that this method is easy to implement because it can be easily incorporated into existing SVPWM algorithm.

REFERENCES