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A Novel Solution for Sensing 3ф 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
$T_{mim} = t_d + t_{rr} + t_{AD}$
Where $t_{d\,=}$ inverter dead time,
$t_{rr\,=}$ diode reverse-recovery time,
$t_{AD\,=}$ 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.

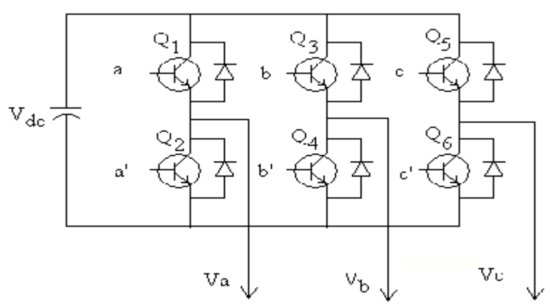

Fig. 1. Three phase voltage source inverter.

(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:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (1)$$

From which one can arrive at equation (2) as follows which determines the phase voltage vector [V_a V_b V_c] where Vdc is the DC supply voltage, or the bus voltage.

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = \frac{1}{3} V_{dc} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (2)$$

(2) *Switching Patterns and the Basic Space Vectors* **:** Space Vector PWM refers to a special switching sequence of the upper three power transistors of a three phase power inverter. It has been shown to generate less harmonic distortion in the output voltages and or currents applied to the phases of an AC motor and provides more efficient use of supply voltage in comparison with direct sinusoidal modulation technique.

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.

$$T_{abc-dq} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \qquad (3)$$

plane perpendicular to the vector $[1, 1, 1]^t$ (the equivalent d-q plane) in a three dimensional coordinate system, the results of which are six non zero vectors and two zero vectors. The nonzero vectors from the axes of a hexagonal as shown in figure 2 & Space vector pattern is also shown in fig 3 and dc link current corresponding to active voltage vector is also tabulated in Table 2.

Table 1.

State	Conducting Transistor
000	T2, T4, T6
001	T2, T4, T5
010	T2, T3, T6
011	T2, T3, T5
100	T1, T4, T6
101	T1, T4, T5
110	T1, T3, T6
111	T1, T3, T5

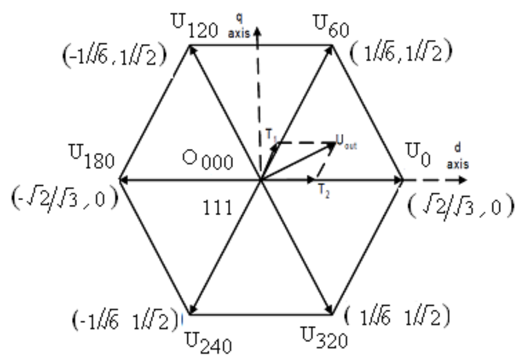

Fig. 2. The basic space vector and switching patterns.

Table 2.

Voltage Vector	**DC Link Current I_{dc}**
V1 = (100)	**$+i_a$**
V2 = (110)	**$-i_c$**
V3 = (010)	**$+i_b$**
V4 = (011)	**$-i_a$**
V5 = (001)	**$+i_c$**
V6 = (101)	**$-i_b$**
V7 = (111)	**0**
V8 = (000)	**0**

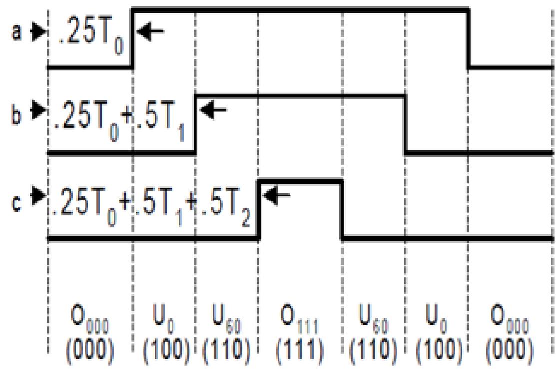

Fig. 3. The basic space vector and switching patterns.
DC Link Current corresponding to Active Voltage Vectors.

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.

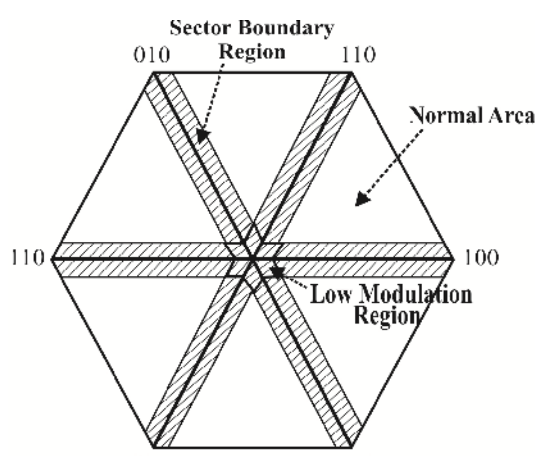

Fig. 4. Unmeasurable areas (Shaded) in the inverter output.

The Above figure shows Example of PWM timing waveforms for basic MVIM algorithm for reference vector in vicinity of (100) active voltage vector with Ts1 = Ts2. Ts1 associated with classical SVPWM plus an additional switching interval Ts2 consisting of three equal measurement intervals Tm.

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 Vs in sector 1 of basic SVPWM is defined as follows:

$$\vec{V_s^*} = \frac{T_0}{T_{S1}}\vec{V_0} + \frac{T_1}{T_{S1}}\vec{V_1} + \frac{T_2}{T_{S1}} = \frac{T_1}{T_{S1}}\vec{V_1} + \frac{T_2}{T_{S1}}\vec{V_2}$$

Where

$Ts1 = T_o + T_1 + T_2 + T_7$ is the PWM switching period.

In comparison the total switching period according to the MVIM algorithm consists of the original Ts1 associated with classical SVPWM plus an additional switching interval Ts2 consisting of three equal measurement intervals Tm. An illustration of the PWM timing waveforms for this total switching period is provided in fig 6.

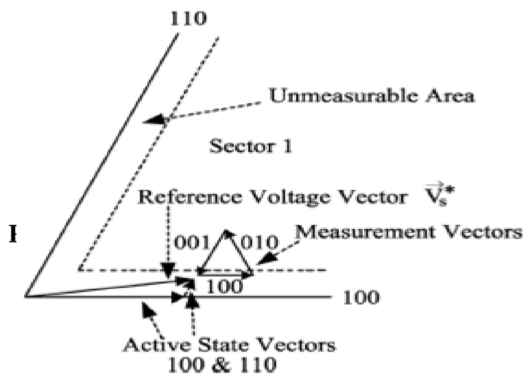

Fig. 5. Basic concept of measurement vectors.

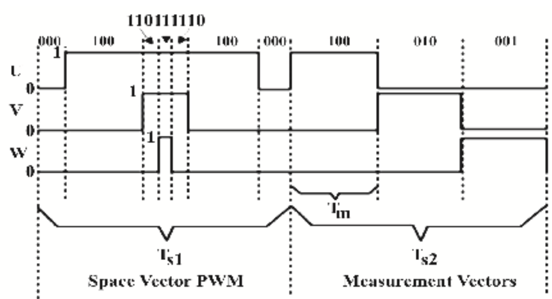

Fig. 6. PWM timing waveforms.

The corresponding reference voltage vector $V_{s\text{-}MV}$ for the space vector plot in fig 5 using the MVIM approach is presented in

$$\vec{V_s^*}\_MV = \frac{T_{S1}}{T_{stot}}\vec{V_s} + \frac{T_M}{T_{stot}}\vec{V_1} + \frac{T_M}{T_{stot}} + \frac{T_M}{T_{stot}}\vec{V_5}$$
$$= \frac{T_0}{T_{stot}}\vec{V_0} + \frac{T_1}{T_{stot}}\vec{V_1} + \frac{T_2}{T_{stot}}\vec{V_2} + \frac{T_7}{T_{stot}}\vec{V_7}$$
$$+ \frac{T_M}{T_{stot}}\vec{V_1} + \frac{T_M}{T_{stot}}\vec{V_3} + \frac{T_M}{T_{stot}}\vec{V_5}$$

Where, V_{s_MV} = the reference voltage vector with MVIM

$T_{s2} = 3T_M$ and T_{stot} = the new total PWM switching period with MVIM

Since $V_1 + V_3 + V_5 = 0$ the expression for Vs-MV can be reduced to

$$\vec{V_s^*}\_MV = \frac{T_1}{T_{stot}}\vec{V_1} + \frac{T_2}{T_{stot}}\vec{V_2} = \frac{T_{s1}}{T_{stot}}\vec{V_s}$$

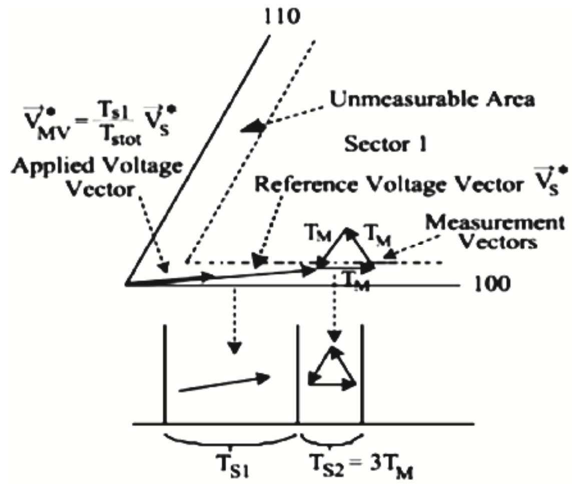

Fig. 7. Impact of measurement vectors on averaged voltage vector amplitude.

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. Tabutated Results

Table 3. Results of simulation of SCST with Measurement Vectors.

SR.NO	M- FACTOR	SVPWM With Measurement vector method	
	Different values of measurement factor	THD of 3 phase current With Single current sensor	THD of 3ø Current measured at three output leads of inverter using 3 current sensor
1.	0.01	0.1802	0.2315
2.	0.04	1.782	0.2283
3.	0.05	0.2378	0.2271
4.	0.1	0.2272	0.2195

Table 4. Results of Simulation of Scst Without Measurement Vectors.

SR.NO	Basic SVPWM Technique without using Measurement vectors	
	THD of current With SCST	THD of 3ø Current measured at three output leads of inverter using 3 current sensor
1.	2.146	0.2327

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

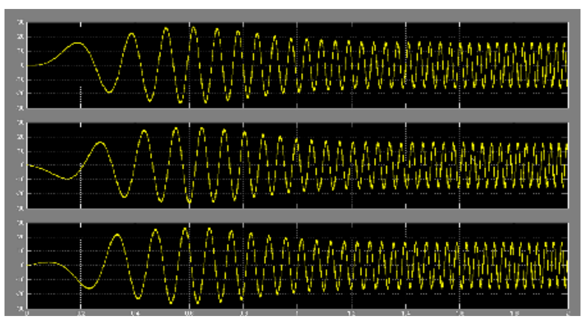

Fig. 8. Three phase current waveform measured at output terminal of voltage source inverter.

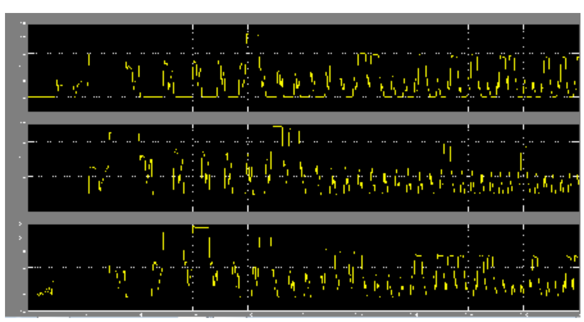

Fig. 9. Three phase current measured at DC link of VSI using SCST but without measurement vectors.

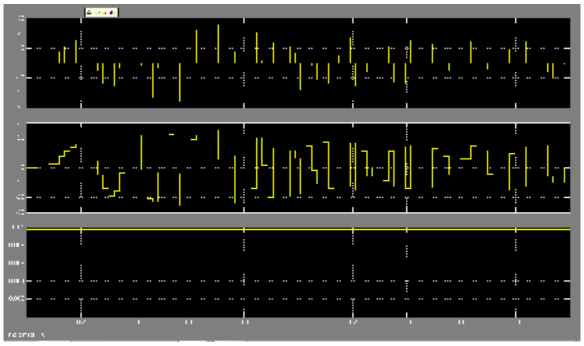

Fig.10. Three phase current measured using SCST & measurement vectors (here measurement factor is 0.01).

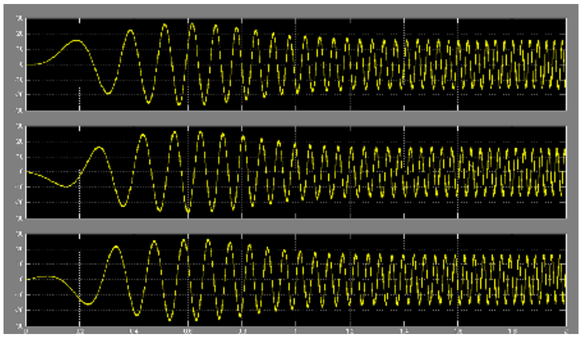

Fig. 11. Three phase current measured using SCST & measurement vectors (here measurement factor is 0.05).

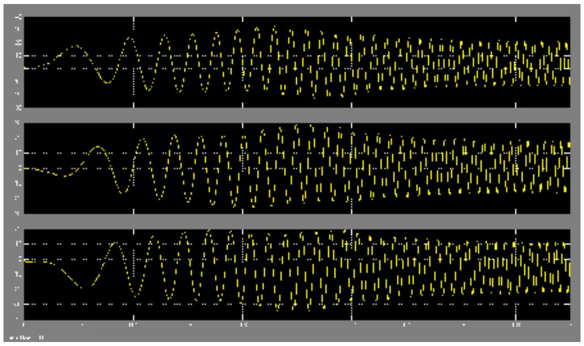

Fig. 12. Three phase current measured using SCST & measurement vectors (here measurement factor is 0.1).

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 t is concluded that:

Measurement factor ≥ 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 3Φ 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

[1]. J. T. Boys, "Novel current sensor for PWM AC drives," *Proc. Inst.Elect. Eng. B*, vol. **135**, pp. 27–32, 1988.

[2]. R.C. Kavanagh, J. M. D. Murphy, and M. G. Egan, "Innovative current sensing for brushless dc drives," in *Proc. 3rd Int. Conf.Power Electron. Variable-Speed Drives (PEVD)*, London, U.K., Jul.1988, pp. 13–15.

[3]. T.C. Green and B. W. Williams, "Derivation of motor line-current waveforms from the dc-link current of an inverter," *Proc. Inst. Elect.Eng. B*, vol. **136**, pp. 196–204, 1989.

[4]. C.D. French, P. P. Acarnley, and A. G. Jack, "Real-time current estimation in brushless DC drives using a single dc link current sensor," in *Proc. 5th Eur. Conf. Power Electron. Appl. (EPE)*, Brighton, U.K., Sep. 13–16, 1993, pp. 7–12.

[5]. F. Blaabjerg and J. K. Pedersen, "An ideal PWM-VSI inverter using only one current sensor in the dc-link," in *Proc. 5th Int. Conf. Power Electron. Variable-Speed Drives (PEVD)*, London, U.K., Oct. 1994, pp.26–28.

[6]. F. Blaabjerg, J. K. Pedersen, U. Jaeger, and P. Thoegersen, "Single current sensor technique in the dc link of three-phase PWM-VS inverters: a review and a novel solution," *IEEE Trans. Ind. Appl.*, vol. **33**, no. 5, pp. 1241–1253, Sep./Oct. 1997.

[7]. W.C. Lee, D.-S. Hyun, and T.-K. Lee, "Novel control method for three-phase PWM rectifiers using a single current sensor," *IEEE Trans.Power Electron.*, vol. **15,** no. 5, pp. 861–870, Sep. 2000.

[8]. S.N. Vukosavic and A. M. Stankovic, "Sensorless induction motor drive with a single dc-link current sensor and instantaneous active and reactive power feedback," *IEEE Trans. Ind. Electron.*, vol. **48**, no. 1, pp. 195–204, Feb. 2001.

[9]. C. Zhang and F. Lin, "A single current sensor control technique for induction motors," in *Proc. Int. Conf. Power Sys. Technol.*, 2002, vol. **4**, pp. 2290–2293.

[10]. D.-C. Lee and D.-S. Lim, "AC voltage and current sensorless control of three-phase PWM rectifiers," *IEEE Trans. Power Electron.*, vol. **17**, no. 6, pp. 883–890, Nov. 2002.

[11]. Hongrae Kim,& Thomas M. Jahns " Phase Current Reconstruction for AC Motor Drives
Using a DC Link Single Current Sensor and Measurement Voltage Vectors." IEEE TRANS. On Power Electronics, Vol. **21**, No. 5, SEPTEMBER 2006.

[12]. J. Holtz, "Pulse width modulation for electronic power conversion," *Proc. IEEE* vol. **82** pp. 1194–1214, Aug. 1994.

[13]. M. Riese, "Phase current reconstruction of a three-phase voltage source inverter fed drive using a sensor in the dc link," presented at the Power Conversion and Intelligent Motion Conference (PCIM'96), 1996.

[14]. J.F. Moynihan, R.C. Kavanagh, M.G. Egan, and J.M.D. Murphy, "Indirect phase current detection for field oriented control of a permanent magnet synchronous motor drive," in *Proc. 4th Eur. Conf. Power Electron. Appl. (EPE)*, Firenze, Italy, Sep. 1991, pp. 3–6.

[15]. J.D. van Wyk, "Power electronics for motion control," *Proc. IEEE*, vol. **82**, pp. 1164–1193, Aug. 1994.

[16]. T.M. Jahns, "Motion control with permanent-magnet AC machines," *Proc. IEEE*, vol. **82**, pp. 1241–1252, Aug. 1994.

[17]. A.B. Plunkett, "A current-controlled PWM transistor inverter drive," in *Proc. IEEE/IAS 1979 Annu. Meeting*, 1979, pp. 785–782.

[18]. F. Petruzziello, G. Joos, and P. D. Ziogas, "Some implementation aspects of line current reconstruction in three phase PWM inverters," in *Proc. IECON'90*, 1990, vol. **2,** pp. 1149–1154.

[19]. Modern Power Electronics and AC Drives, by *Bimal K. Bose* Prentice Hall Publishers 2001.

[20]. Power Electronics by *Dr. P.S. Bimbhra* Khanna Publishers, New Delhi, 2003. 3rd Edition.

[21]. A Power Electronics Handbook by *M.H. Rashid* Academic Press 2001.