3-Phase Current Reconstruction of
Permanent Magnet Synchronous Motor Drives
Using a Single DC-Link Current Sensor

Cheng-Yu Hsieh, Wen-Chun Chi, Ming-Yang Cheng,*
Wei-Liang Kuo, and Wei-Leng Wu

Department of Electrical Engineering, National Cheng Kung University, Tainan, Taiwan

In the application of conventional 3-phase current reconstruction methods using a single DC-link current shunt, the self-switch configuration of space vector pulse width modulation (SVPWM) may cause a problem of insufficient measuring time in certain regions. To cope with this problem, in this paper, we propose a switching strategy that exploits the advantages of SVPWM, the measurement vector insertion method (MVIM), and the pulse-width modulation method without using the null switching states method (NSVM). In the proposed switching strategy, the MVIM is employed in the low-modulation-ratio region and the sector boundary region of the middle-modulation-ratio region, while the NSVM is adopted in the sector boundary region of the high-modulation-ratio region. In addition, we used Matlab/Simulink in this study to construct a simulated environment to conduct an in-depth study of the differences among various current construction methods as well as the size of the immeasurable region.

1. Introduction

The 3-phase current information of the permanent magnet synchronous motor (PMSM) plays a crucial role in closed-loop control as well as in overcurrent protection, DC-link current short protection, and ground fault protection. The safety of PMSM and its drive can be ensured if one can use 3-phase current feedback information effectively. Common approaches for measuring 3-phase currents use two current sensors in series with phase winding. Although the approach is easy to implement, it is not cost-effective. Moreover, to ensure accuracy in phase current reconstruction, parameters such as current magnification, DC offset, and filter cutoff frequency for the two current sensors must be in good agreement. Otherwise, when reconstructing the current of the third phase, differences in parameter values may lead to errors in the reconstructed phase current so that the output ripple of the current loop may increase.[1] A possible approach to coping with this problem is to use a single DC-link current sensor to retrieve phase current information. Since only one current sensor is used, the cost is lower and the problem of deviation in parameter values for different current sensors does not exist.

Suppose that the 3-phase current reconstruction technique is implemented on the basis of a single DC-link current sensor and space vector pulse width modulation (SVPWM). When the

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*Corresponding author: e-mail: mycheng@mail.ncku.edu.tw

voltage space vector is located in the sector boundary region of the voltage vector, or when the modulation ratio of the reference voltage vector is too small, the component of the reference voltage vector will be too small. As a result, the power switching conduction time is so short that the time duration of the voltage vector is shorter than the minimum time needed for measuring the phase current. Since in this region the phase current cannot be correctly measured,[2] this leads to error in the reconstruction of the 3-phase current. To solve these problems, many approaches for dealing with the problem of 3-phase current reconstruction using a single DC-link current sensor have been proposed. In this paper, we describe an in-depth study on several existing modified SVPWM-based reconstruction methods. The advantages and drawbacks of these existing approaches are analyzed. On the basis of these results, a switching strategy has been developed, which exhibits the advantages of SVPWM, a pulse width modulation method without using the null switching states method (NSVM),[5–7] and the measurement vector insertion method (MVIM).[8] In particular, MVIM is employed in the low-modulation-ratio region and the sector boundary region of the middle-modulation-ratio region, while the NSVM is used in the sector boundary region of the high-modulation-ratio region.

2. Methods

2.1 Phase current reconstruction limitation of SVPWM

Assume that the motor drive control of a PMSM is implemented using SVPWM. If the space vector of the inverter is an effective voltage vector, one can determine to which phase the current signal measured by the DC-link current sensor belongs. By sampling the resultant reference voltage vector of two effective vectors during one SVPWM period and applying the principle of a balanced 3-phase system, one can reconstruct the 3-phase currents based on the phase current measured by the DC-link current sensor. To correctly reconstruct the 3-phase currents, the reference voltage vector of the inverter must satisfy the following two inequalities:[9]

$$T_{acq} \leq T_1 = T_z \cdot m \cdot \frac{\sin(\pi/3 - \theta_e)}{\sin(\pi/3)}, \tag{1}$$

$$T_{acq} \leq T_2 = T_z \cdot m \cdot \frac{\sin(\theta_e)}{\sin(\pi/3)}, \tag{2}$$

where T_{acq} is the minimum detection time of the phase current, and T_1 and T_2 are the times needed for the conduction of the space vectors $\overrightarrow{V_1}$ and $\overrightarrow{V_2}$, respectively. The value of T_z is half of the switching time for a symmetric SVPWM. If either Eqs. (1) or (2) is not satisfied, the reconstruction of the 3-phase currents may be in error. Figure 1 illustrates the region of the reference voltage vector that can reconstruct the 3-phase currents under SVPWM. The analysis of the region for which the reference voltage vector is located is provided in the following:

In region (A) of Fig. 1, one can reconstruct the 3-phase currents correctly. In this region, both the time duration of the effective vectors of T_1 and T_2 are larger than that of T_{acq}. If the reference voltage vector is located in this region, one can reconstruct the 3-phase currents without performing any change with respect to the output signal of SVPWM.

In region (B) of Fig. 1, one cannot reconstruct the 3-phase currents correctly. This region is commonly called the sector boundary region.[3,4] In this region, only one of the time durations of
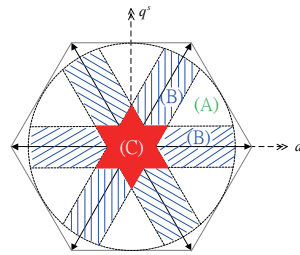
Fig. 1.   (Color online) Illustrative diagram of region of 3-phase current reconstruction using SVPWM.

the effective vectors of T_1 and T_2 is larger than T_{acq}. As a result, only the current information from one phase of SVPWM is available. That is, the reconstruction of the 3-phase currents is impossible.

In region (C), one cannot reconstruct the 3-phase currents correctly. This region is commonly referred to as the low-modulation-ratio region,[3,4] in which both the time durations of the effective vectors of T_1 and T_2 are smaller than T_{acq}. Therefore, no phase current information can be acquired during the SVPWM period.

2.2   Modulation method without using NSVM

As shown in Fig. 1, regions (B) and (C) are the regions for which the 3-phase current reconstruction technique using a single DC-link current sensor fails (defined as the immeasurable region in this paper). To reduce the size of regions (B) and (C), several previous studies have proposed a modified approach. That is, when the reference voltage vector is located in the immeasurable region, the output signal of SVPWM is provided by NSVM.[5–7] Moreover, phase current detection is carried out with respect to the output signal provided by NSVM. As shown in Fig. 2, in the NVSM approach, V_0 and V_7 of SVPWM are replaced by V_M and $V_{\overline{M}}$, respectively.

2.3   MVIM

In Ref. 8, the MVIM is proposed to overcome the difficulty in which the NSVM may lead to large current harmonics in the low-modulation-ratio region. In the MVIM, if the reference voltage vector is located in the immeasurable region of the SVPWM, then a measurement vector is inserted in the output signals, and the current detection is carried out at this measurement vector as shown in Fig. 3. When the switching frequency is high, the total output power of these three effective vectors is zero for the motor itself. The time duration T_{mv} for these three effective vectors is decided by the minimum detection time of the phase current T_{acq}.

3.   Results

To conduct a complete and extensive analysis of different 3-phase current reconstruction methods, we used Matlab/Simulink to construct a simulated environment to investigate the differences among various current construction methods as well as the size of the immeasurable region and current harmonics. Figure 4 shows the simulation results for the case of the 0.95 (p.u.) reference voltage vector, while Fig. 5 shows the simulated results for the case of the 0.2 (p.u.) reference voltage vector. The results indicate that the NVSM can indeed reduce the size of the immeasurable region in the sector boundary region and result in small current harmonics in the
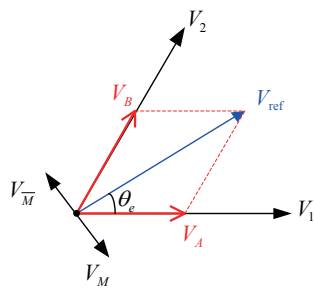
Fig. 2. (Color online) Illustrative diagram of NSVM in the voltage vector space.
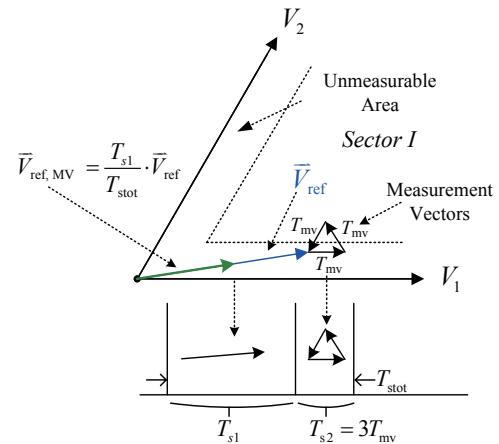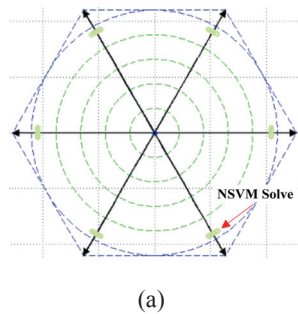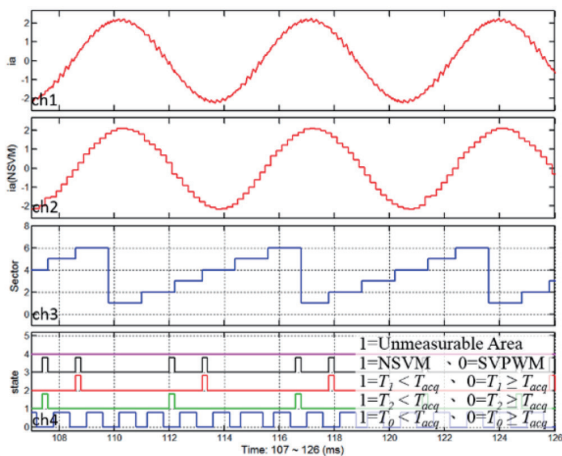

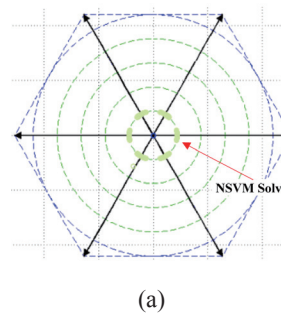Fig. 3. (Color online) Illustrative diagram of MVIM in the voltage vector space.
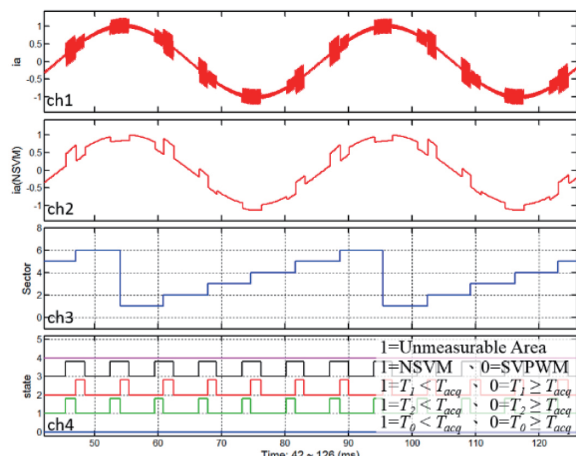

(a)

(a)

(b)

(b)

Fig. 4. (Color online) Simulated results of NSVM in the high-modulation-ratio region [F_{pwm} = 5 kHz and V_{ref} = 0.95 (p.u.)]. (a) Immeasurable region and (b) simulated waveform.

Fig. 5. (Color online) Simulated results of NSVM in the low-modulation-ratio region [F_{pwm} = 5 kHz and V_{ref} = 0.2 (p.u.)]. (a) Immeasurable region and (b) simulated waveform.

high-modulation-ratio region. However, the NVSM results in large current harmonics in the low-modulation-ratio region. Therefore, the NVSM is not suitable for the low-modulation-ratio region. In contrast, Figs. 6 and 7 show the simulated results of MVIM in the middle- and low-modulation-ratio regions, respectively. These results reveal that the MVIM can be used to reconstruct the 3-phase currents in the low-modulation-ratio region, resulting in small current harmonics. Consequently, the MVIM can be adopted in the low-modulation-ratio region to reconstruct the 3-phase currents.

4.　Discussion

　　Table 1 lists the advantages and drawbacks of different 3-phase current reconstruction methods such as SVPWM, NSVM, and MVIM. Clearly, each method has its own suitable modulation ratio region. To reduce the size of the immeasurable region, we propose a switching strategy that exploits the advantages of the three 3-phase current reconstruction methods. In particular, by considering the advantages and drawbacks of the three methods, the proposed approach adopts different current reconstruction methods in different regions of the space vector as listed in Table 2 and shown in Fig. 8. For example, if the reference voltage vector is located in region (A), then the original SVPWM-based method is adopted to reconstruct the 3-phase current. In contrast, if the
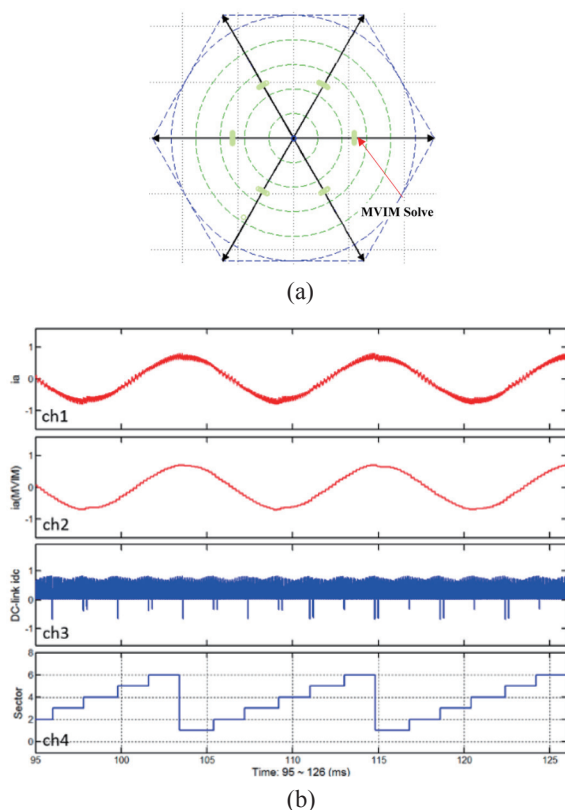

(a)

(b)

Fig. 6.　(Color online) Simulated results of MVIM in the middle-modulation-ratio region [F_{pwm} = 5 kHz and V_{ref} = 0.5 (p.u.)]. (a) Immeasurable region and (b) simulated waveform.
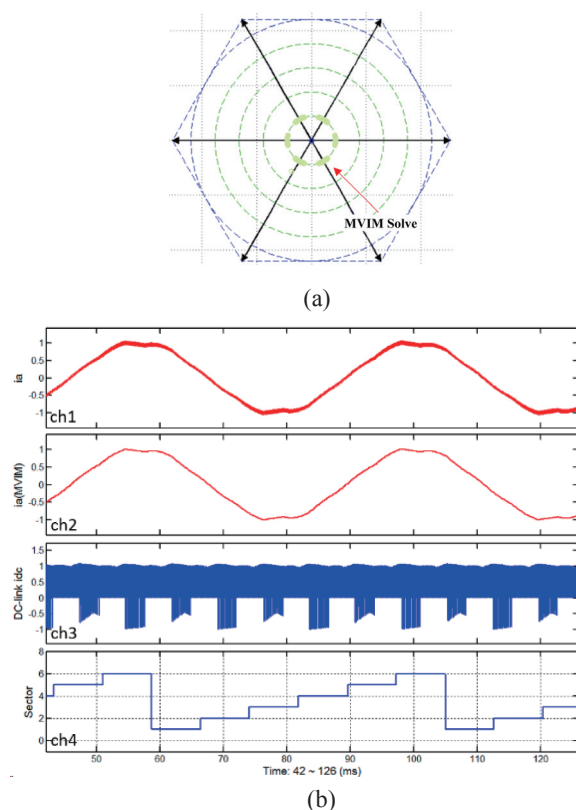

(a)

(b)

Fig. 7.　(Color online) Simulated results of MVIM in the low-modulation-ratio region [F_{pwm} = 5 kHz and V_{ref} = 0.2 (p.u.)]. (a) Immeasurable region and (b) simulated waveform.

Table 1
Drawbacks and advantages of three 3-phase current reconstruction methods using a single DC-link current sensor.

Methods	Comparison	Description
SVPWM	Advantage	Lowest current harmonics.
	Drawback	Immeasurable regions consist of the sector boundary region of the middle- and high-modulation-ratio regions and the low modulation-ratio region.
NSVM	Advantage	Small immeasurable regions in the middle- and high-modulation-ratio regions.
	Drawback	Large current harmonics in the low-modulation-ratio region.
MVIM	Advantage	Can reconstruct 3-phase current in the middle- and high-modulation-ratio regions.
	Drawback	The magnitude of the reference voltage vector is restricted in the high-modulation-ratio region.

Table 2
The proposed switching strategy for 3-phase current reconstruction.

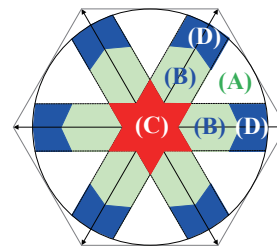| Region	Adopted methods
(A)	SVPWM
(B)	NSVM or MVIM
(C)	MVIM
(D)	NSVM

Fig. 8.   (Color online) Illustrative diagram of the proposed switching strategy.

reference voltage vector is located in regions (C) or (D), then MVIM (or NSVM) is adopted. If the reference voltage vector is located in region (B), either MVIM or NSVM can be used.

5.   Conclusions

In this study, we constructed a simulated environment based on Matlab/Simulink to investigate the advantages and drawbacks of several existing 3-phase current construction methods. On the basis of the analysis of the Matlab/Simulink simulation results, in this study, we proposed a switching strategy that exploits the advantages of three 3-phase current reconstruction methods. In particular, by analyzing the advantages and drawbacks of the 3-phase current reconstruction methods, the proposed switching strategy can be used to determine a suitable 3-phase current reconstruction method for different regions of the space vector to provide a wider 3-phase current reconstruction range than other existing methods.

References

1   H. S. Jung, S. H. Hwang, J. M. Kim, C. U. Kim, and C. Choi: IEEE Trans. Ind. Appl. **42** (2006) 1249.
2   J. Moynihan, R. Kavanagh, M. Egan, and J. Murphy: Proc. Conf. Power Electron. Appl. 1992 (IEEE, New York, 1992) pp. 641–641.
3   W. C. Lee, T. K. Lee, and D. S. Hyun: IEEE Trans. Ind. Electron. **48** (2001) 491.
4   Y. Gu, F. Ni, D. Yang, and H. Liu: IEEE Trans. Ind. Electron. **58** (2011) 5186.
5   Y. S. Lai: Proc. Conf. IEEE Power Eng. Soc. 1999 (IEEE, New York, 1999) pp. 35–40.
6   Y. S. Lai and F. S. Shyu: IEEE Trans. Ind. Appl. **40** (2004) 1605.
7   Y. S. Lai, P. S. Chen, H. K. Lee, and J. Chou: IEEE Trans. Ind. Appl. **40** (2004) 1613.
8   H. Kim and T. M. Jahns: IEEE Trans. Power Electron. **21** (2006) 1413.
9   Y. V. S. Reddy, T. B. Reddy, and M. V. Kumar: Proc. Int. Conf. Power Electron. Drives Energy Syst. 2006 (IEEE, New York, 2006) pp. 1–5.