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Hybrid Pulse Width Modulation Strategy for Wide Speed Range in IPMSM with Low Cost Drives

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Abstract – The control performance of hybrid PWM inverter using a phase current measurement is presented in this paper. The hybrid PWM technique consists of space vector pulse width modulation (SVPWM) and six-step voltage control operation. The SVPWM is performed to reduce the harmonic components in the low speed region, and the six-step modulation is applied to increase the maximum speed of the IPMSM in the high speed region. Therefore, it is possible to obtain a great performance in both the low speed range and high speed range. However, the six-step modulation cannot be completely implemented, since the inverter that includes the lag-shunt sensing method has an immeasurable current region. In this paper, a quasi-six-step modulation using a modified voltage vector is proposed. The validity and usefulness of the proposed PWM technique is verified by MATLAB/Simulink and experimental results.

Keywords: Hybrid pulse width modulation, Quasi-six-step modulation, Voltage utility maximization, Field weakening, Low cost IPMSM drive

1. Introduction

Interior permanent magnet synchronous motors (IPMSMs) have a number of advantages mainly in terms of weight and volume, which can be significantly reduced for a given output power. They also exhibit higher efficiency than other motors and have been widely used in various fields. The use of IPMSM in low-cost drives has also increased due to its applications in home appliance products. However, the low-cost drives have the disadvantage of having immeasurable current regions. Therefore, many studies have been conducted to develop a current sensing region. [1, 2] These algorithms, however, are not suitable for low-cost inverters because the implementation is highly complex.

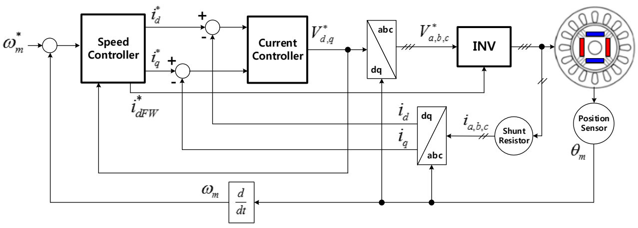
In this paper, a hybrid pulse width modulation (PWM) of an IPMSM for low cost drives is proposed. The proposed modulation technique has greater voltage-utilization than others, and therefore, IPMSM can achieve a higher final speed. This paper also proposes quasi-six-step modulation.

2. Basic Theorem of the Low Cost IPMSM Drivers

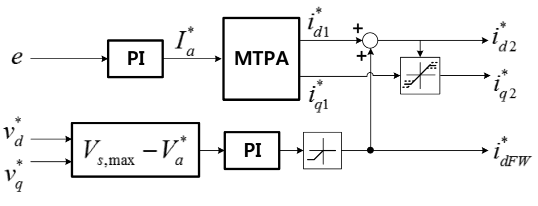
This chapter covers the basic theorem to explain Hybrid PWM method proposed in this paper. It will explain about the field weakening control to increase speed above base rpm and the characteristics of low cost inverter. Lastly, it will analyze maximum speed in accordance with the voltage modulation system of IPMSM.

2.1 The field weakening control

A field weakening control is performed to increase the speed range of IPMSM. IPMSM can be operated on high speed by flowing negative d- axis current through the field weakening control. Many techniques for field weakening control for IPMSM have been published [3]; in this paper, the field weakening control is performed by regulating the voltage loop as shown in Fig. 1. [4] At the less than base speed, the magnitude of the reference output voltage



(a) The overall control system



(b) The speed Controller with FW

Fig. 1. Block diagram of IPMSM drive system [4]

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is less than $V_{s,max}$ and thus the field weakening current i^*_{dFW} is zero. So, maximum torque-per-ampere control is performed. When the magnitude of the reference output voltage is larger than $V_{s,max}$, i^*_{dFW} is increase toward the negative direction for flux weakening operation. In this paper, the selection between the SVPWM and quasi-six-step operation will be depended on the results from i^*_{dFW}. When i^*_{dFW} is zero, SVPWM is conducted, and the quasi-six-step operation is performed in the opposite case.

2.2 The lag-shunt current SENSING method

Three phase currents can be measured through one inexpensive shunt in the dc bus, or three phase shunt in the invert output sides or three shunt resistors in the low-side switches. Especially, the three shunt sensing technology, called a lag-shunt sensing method, is known for its great performance in cost-effectiveness. Therefore, it is widely used in low cost applications. [2] Fig. 2 shows a three-phase inverter with lag-shunt resistors. However, lag-shunt sensing method cannot acquire phase currents in certain operating conditions. To measure the electric current of three-phase, electric current should flow into more than 2 shunt resistors, but electric current is not detected in case it flows into only 1 shunt resistor among 3 shunt resistors. Thus, an immeasurable current region occurs as in Fig. 3.

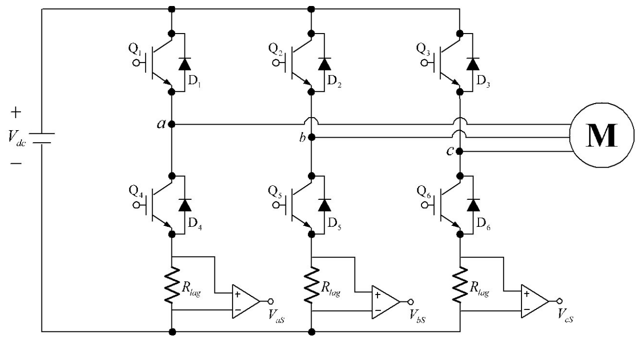


Fig. 2. A three-phase inverter driving IPMSMs with current sampling circuit

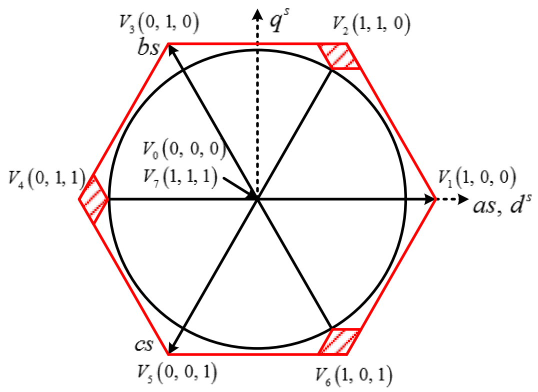


Fig. 3. Immeasurable current region in lag-shunt current sensing method.

The immeasurable current region can be determined by the minimum time it takes to sense the current T$_{sm}$. T$_{sm}$ consists of inverter dead time, delay time of the current detection circuit and A/D converter sampling time.

2.3 The maximum speed of IPMSM

The voltage equations of IPMSM in the synchronous d-q frame are given by using Clarke's and Park's transformations [5]

$$\begin{bmatrix} v^r_{ds} \\ v^r_{qs} \end{bmatrix} = \begin{bmatrix} R_a & -\omega L_q \\ \omega L_d & R_a \end{bmatrix} \begin{bmatrix} i^r_{ds} \\ i^r_{qs} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_e \Psi_a \end{bmatrix} \tag{1}$$

The terminal voltage supplied to the motor by the inverter is limited as follows

$$V_a = \sqrt{v^{r\,2}_{ds} + v^{r\,2}_{qs}} \le V_{am} \tag{2}$$

where V_{am} is the maximum output voltage of the inverter and depends on DC link voltage. It can be obtained according to the voltage modulation method.

$$V_{am(SVPWM)} = \frac{V_{dc}}{\sqrt{3}},\ V_{am(DPWM)} = \frac{V_{dc}}{\sqrt{3}},\ V_{am(six-step)} = \frac{2V_{dc}}{\pi} \tag{3}$$

Neglecting the voltage drop of the stator resistance, the voltage limit ellipse can be expressed by (1) and (2).

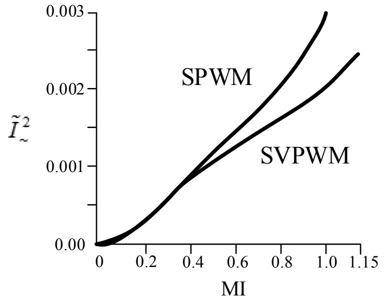
$$\sqrt{\left(L_d i^r_{ds} + \Phi_a\right)^2 + \left(L_q i^r_{qs}\right)^2} = \left(\frac{V_{am}}{\omega}\right) \tag{4}$$

The maximum speed of IPMSM can be obtained by the contact of current limit circles and voltage limit ellipse. It is expressed by substituting $i^r_{ds} = -I_{am}$ and $i^r_{qs} = 0$ into (4).

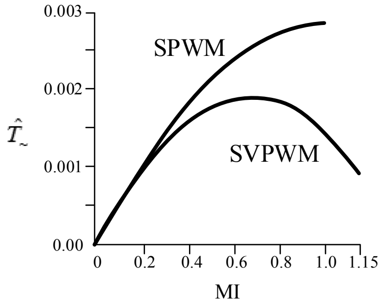
$$\omega_c = \frac{V_{am}}{\Phi_a - L_d I_{am}} \tag{5}$$

3. Hybrid Pulse Width Modulation for Low Cost Drivers

Because at least two low-side switches are required to measure the three phase current, discontinuous pulse width modulation (DPWM) is most commonly applied to low cost drives. It is possible to increase the speed limit by utilizing six-step modulation. However, it causes noise and vibration, especially in the low speed range including many harmonics. [6] Therefore, a low modulation index will lower harmonic content by driving the motor in SVPWM and increase the speed range by changing into a six-step modulation in the field weakening area.



(a) Square of rms harmonic current



(b) Peak values of torque harmonics

Fig. 4. Characteristics of SPWM and SVPWM [7]

3.1 SVPWM at low modulation index

In the low-speed region that has a low voltage modulation index, SVPWM is used. Among other PWM techniques, SVPWM contains the least harmonic components and has a wide linear modulation interval. [7] The harmonics characteristics of SVPWM are compared with those of SPWM in Fig. 4; SVPWM, therefore, operates below the base speed. It should be noted that SVPWM is difficult to implement because the on-time of the switches needs to be operated in a fixed sequence. However, this problem can be fixed simply by using the offset voltage, using the following equation.

$$V_{offset} = -\frac{V_{\max} + V_{\min}}{2} \tag{6}$$

3.2 Six-step modulation at high modulation index

When the voltage of power supply goes higher than $V_{dc}/\sqrt{3}$, the voltage limit, while driving the motor in SVPWM, it will go over the linear modulation section. As a result, field weakening control is performed to widen the speed range. However, a higher output can be obtained if the motor is driven in six-step modulation in the field weakening area because voltage use rates increases by 10.25% compared to SVPWM. Therefore, the output of motor can be enhanced by driving it in six-step modulation in the area above base rpm. [8]

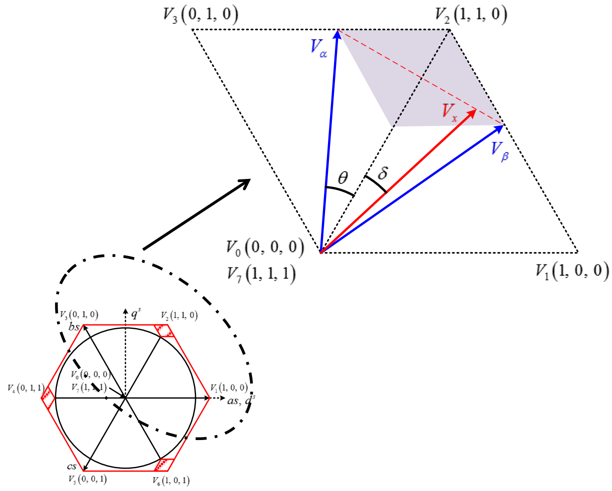


Fig. 5. The modified voltage vectors of V_2

3.3 Quasi-six-step modulation for the low cost drives

Since the lag-shunt sensing inverter has an immeasurable region, it is impossible to induce the voltage vector V_2, V_4, and V_6; the six-step modulation, therefore, cannot be performed. However, by modifying the voltage vector, nearly the same control as the square wave can be achieved. Fig. 5 enlarges the surroundings of voltage vector V_2 among the immeasurable current region. In Fig. 5, the colored portion indicates the immeasurable region. Among voltage vectors that can be induced instead of V_2, the ones with the highest magnitude are defined as V_α and V_β. The magnitude of V_α and V_β is represented as follow

$$V_{\alpha m} = V_{\beta m} = \frac{V_{dc}}{2}\sqrt{T_{sm}^2 - T_{sm} + 1} \tag{7}$$

The larger the value of voltage vector, the more operating high output. Depending on the load conditions, the motor can show better characteristics on a certain location between V_α and V_β. Thus, by using V_α and V_β vector, it can operate adjusting V_x vector in accordance with the load condition. The magnitude of V_x vector is obtained as

$$V_{xm} = \frac{V_{dc}}{4}\left(2 - T_{sm}\right) \cdot \frac{1}{\cos\delta} \tag{8}$$

The speed limit can be increased by applying the modified voltage vectors V_α, V_β, and V_x instead of V_2 for six-step modulation in the lag-shunt sensing inverter.

4. Simulation and Experimental Results

The simulation and experiment were implemented on the 750W IPMSM servomotor. The specifications of the

Table 1. Specifications of IPMSM

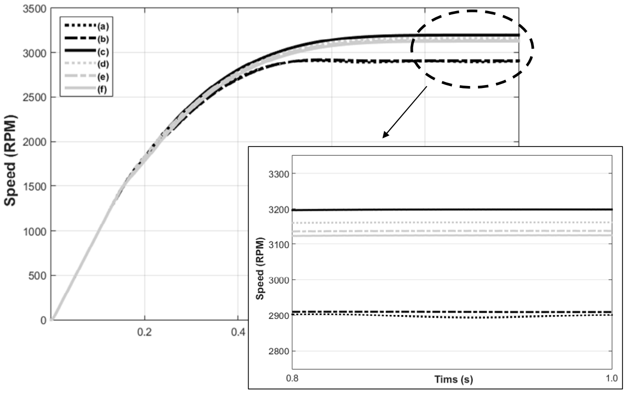
Parameter	Value	Unit
N_p	4	
V_{dc}	50	V
I_{am}	4	A
R_a	0.82	Ohm
T_{max}	2.28	Nm
Φ_a	0.098	Wb
L_d	14	mH
L_q	18	mH

IPMSM are presented in Table 1. The base speed of the test motor is 1070rpm. Applying the Eq. (5) for the test motor, the maximum speed is about 3300rpm when operated six-step modulation. To analyze the maximum speed with voltage modulation methods, 3500rpm which is more than theoretical value was given to the reference speed.

4.1 Simulation results

In order to verify the performance of the proposed algorithm, the simulation is performed by MATLAB / Simulink. A simulation model that consists of the IPMSM is built in MATLAB. Fig. 6 (a) and (b) demonstrate that the final speed is similar because SVPWM and DPWM have the same voltage utilization rate. Through Fig. 6 (c), it could be confirmed that the speed increased by 10.27% compared to DPWM as six-step modulation was applied in high modulation index. Fig. 6 (d), (e), and (f) show the results of quasi-six-step modulation, representing $\delta=+\theta$, $-\theta$, 0 respectively. While the speed decreased compared to Fig. 6 (c), it increased by 9.0% compared to SVPWM and DPWM. In Fig. 6 (d), the speed was the highest because the motor is R-L load.

4.2 Experimental result



(a) SVPWM (b) DPWM (c) Six-Step Modulation in FW; (d) Quasi-Six-Step Modulation by V_α ; (e) Quasi-Six-Step Modulation by V_β ; (f) Quasi-Six-Step Modulation by V_x (δ=0°)

Fig. 6. The simulation final speed (ω_m* = 3,500 rpm)

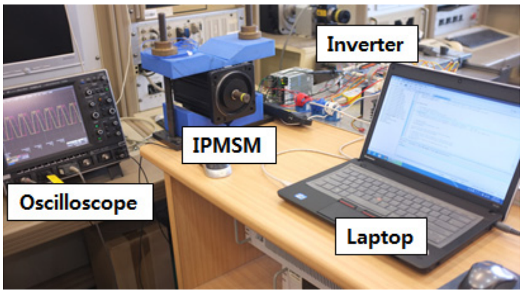
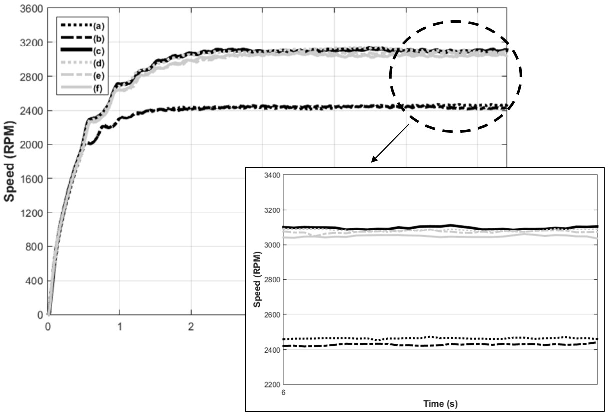


Fig. 7. Experimental test setup



(a) SVPWM (b) DPWM (c) Six-Step Modulation in FW ; (d) Quasi-Six-Step Modulation by V_α ; (e) Quasi-Six-Step Modulation by V_β ; (f) Quasi-Six-Step Modulation by V_x (δ=0°)

Fig. 8. The experimental final speed (ω_m* = 3,500 rpm)

Table 2. CPSR of the test motor using different PWM methods

PWM Method	Simulation		Experiment	
	Final Speed [rpm]	CPSR	Final Speed [rpm]	CPSR
SVPWM	2900	2.71	2462	2.30
DPWM	2900	2.71	2440	2.28
Hybrid PWM	3198	2.99	3102	2.90
V_α	3161	2.95	3074	2.87
V_β	3137	2.93	3070	2.87
V_x (δ=0°)	3125	2.92	3060	2.86

The hybrid PWM algorithm is processed in a control board based on the Digital Signal Processor TMS320F28335. The modulation methods are carried out by triangular carrier comparison using a carrier frequency of 10 kHz, and the minimum time for the current sensing T_{sm} is 8μs. The experimental test setup is shown in Fig. 7.

Fig. 8 (a) and (b) show the final speed of SVPWM and DPWM. As in the simulation, both have similar values. Fig. 8 (c) shows the result of six-step modulation in field weakening and increased by 25.36% compared to Fig. 8 (a) and (b). Fig. 8 (d) ~ (f) shows the use of modified voltage vectors applied in low cost inverter, and while the speed decreased compared to Fig. 6 (c) it increased by 23.95% compared to Fig. 6 (a) and (b).

Table 2 shows constant power speed ratio (CPSR) of the test motor depending on PWM Methods. [9]

5. Conclusion

In this paper, the voltage utility maximization algorithm based on a lag-shunt sensing method is proposed. The proposed hybrid PWM strategy is verified with a servomotor comparing DPWM. And quasi-six-step is performed by applying the modified voltage vectors, since the lag-shunt sensing inverter has an immeasurable current region. The usefulness and effectiveness of the algorithm is confirmed by MATLAB/Simulink, and the validity of the voltage utility maximization algorithm is verified by the servomotor.

Acknowledgements

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