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# PWM control method to improve the voltage utilization rate of the inverter.

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**ABSTRACT**: Inverters that drive in-vehicle motors are required to be driven efficiently and stably in a wide operating range from low-speed large torque to high-speed high-induced voltage. In order to improve the efficiency of the inverter, it is necessary to further reduce the output current for the same torque by improving the voltage utilization rate. In this paper, we propose a PWM control method that improves the voltage utilization rate of the inverter, and confirm its effectiveness by experiments. In addition, the proposed method is compared with other control methods that realize 1-pulse, and points to be further improved in the proposed method are considered.

**KEY WORDS**: power electronics, motor drive, inverter, pwm

## 1. INTRODUCTION

In order to accelerate the electrification of automobiles, it is becoming important to develop inverters that drive electric motors.

PWM (Pulse Width Modulation) control is adopted for the inverter in order to realize highly accurate torque control of the electric motor. Since electric motors for automobiles are required to rotate at high speed due to the pursuit of miniaturization, inverters are required to have not only high efficiency but also stable motor control over a wide operating range [(1)].

As part of this, improvement in the voltage utilization rate of the inverter output voltage is required, and the modulation method shown in Fig.1 is generally adopted.

In sine wave modulation (three-phase modulation), as shown in Fig.2, the actual inverter output voltage (fundamental wave component) has a characteristic of a proportional relationship with the modulation factor command value.

However, in the over modulation method, when an attempt is made to generate a PWM signal by comparing a sinusoidal modulated signal with a triangular wave carrier, the relationship between the modulation factor command value and the actual inverter output voltage becomes a non-linear characteristic. Therefore, there is a problem that the control performance deteriorates when continuously controlling from the sine wave modulation method to the 1-pulse (square wave) method.

Further, in the 1-pulse method, only the voltage phase angle can be operated for torque control. Therefore, as a method of generating a voltage command value in the torque control algorithm of the motor, it is generally operated by switching from vector control to load angle control [(2)]. However, due to the discontinuous switching of different control methods, tuning for suppressing torque and current shocks is required.

Furthermore, dedicated hardware (FPGA, etc.) may be required to manage the switching timing of 1-pulse.

As one method to solve the above difficulty, we propose a PWM control method that improves the voltage utilization rate to the same level as the 1-pulse method with linear characteristics only by using the PWM signal generation function by comparing the triangular waves of the microcomputer and software control calculation. The effectiveness of the proposed PWM control method will be shown by experiments.

In addition, the proposed method is compared with other control methods that realize 1-pulse, and points to be further improved in the proposed method are considered.

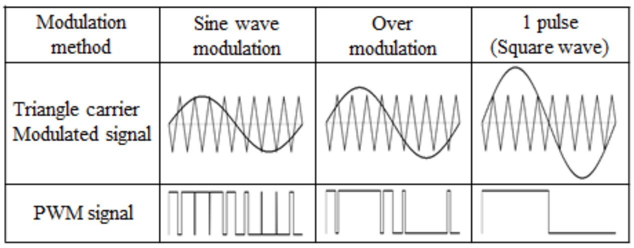



Fig. 1 Modulation method of the inverter.

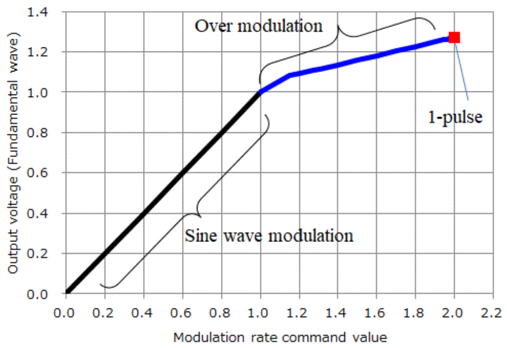



Fig. 2 Relationship between modulation rate command value and actual output voltage.

## 2. OUTLINE OF INVERTER CONTROL

The configuration of the motor control system is shown in Fig. 3. High-performance driving can be realized by performing current control on two rotating axes (d-q axes) corresponding to the rotation angle of the rotor of the AC motor. In the current detection circuit, the analog signals iu, iv, iw of the current detected by the current detectors of the respective phases are fetched into the CPU and A/D conversion is performed. The current detection values Iu, Iv, Iw of the respective phases converted into the digital signals are converted into the d-q axis current detection values Id, Iq by using the angle θ. The d-q axis voltage command values $Vd^*$, $Vq^*$ are calculated by calculating the difference between the current command values $Id^*$, $Iq^*$ and the current detection values Id, Iq by the current regulator, and the phase voltage command values $Vu^*$, $Vv^*$, $Vw^*$ . Thereafter, the input voltage detection value Edc is used for reference conversion to the modulation factor command values $\lambda u^*$, $\lambda v^*$, $\lambda w^*$. The PWM calculation unit generates a gate signal by comparing the modulation factor command value and the triangular wave carrier and controls the current to the command value by the switching operation of the inverter.

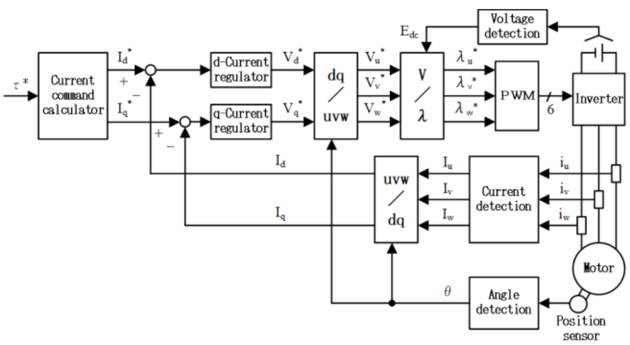



Fig. 3 Block diagram of the inverter vector control system.

## 3. SYNCHRONOUS 1 PULSE DRIVE

### 3.1. Synchronous carrier frequency

As described above, the PWM control block adopts the triangular wave comparison PWM method. When the carrier frequency is relatively low with respect to the output fundamental wave frequency, the number and width of positive and negative pulses become asymmetric. That is, the voltage becomes positive and negative asymmetric, and the current cannot be controlled stably. Therefore, asynchronous PWM is used in the low frequency range of the inverter, and synchronous PWM is used in the high frequency range.

By synchronizing the inverter output and the carrier triangle wave, the control is stabilized without increasing the carrier frequency more than necessary (without increasing the switching loss). As shown in Figure 4, in asynchronous PWM, the carrier frequency is set to a fixed value, and in synchronous PWM control, the frequency of the triangular wave carrier is controlled to be 9 times the inverter output fundamental wave frequency.

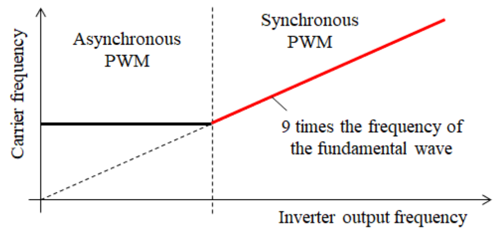



Fig. 4 Carrier frequency operation method.

### 3.2. Synchronous PWM control for 1 pulse (Square wave)

Fig.5 shows a synchronous PWM signal generation method for improving the voltage utilization rate. The proposed method is a method of reducing the number of pulses according to the voltage command amplitude, and the details will be described below.

#### 3.2.1. Synchronous 9 pulse

The synchronous 9 pulses are controlled so that the number of pulses for one cycle of the voltage fundamental wave is 9, as shown in Fig.5 (a).

The PWM signal is generated by comparing the synchronized triangular wave carrier with each phase modulation factor command value calculated by sinusoidal modulation (three-phase modulation) or two-phase modulation.

#### 3.2.2. Synchronous 5 pulse

Synchronous 5 pulses are generated by controlling the pulse width x (phase angle) in a specific adjustment section of the voltage command phase. As a result, the PWM signal keeps 5 pulses and variably controls the effective output voltage value.

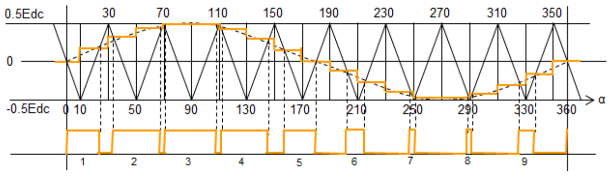
The width x is calculated by the following equation.

$$x = \sin^{-1}\left(\frac{1}{2} - \frac{\pi}{2\sqrt{6}}\frac{V_1^*}{E_{dc}}\right) \tag{1}$$

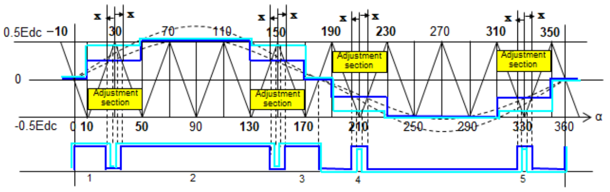
$$V_1^* = \sqrt{V_d^{*2} + V_q^{*2}} \tag{2}$$

$V_d^*$: d-axis voltage command value (Absolutely converted)

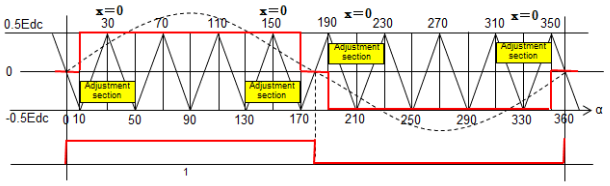
$V_q^*$: q-axis voltage command value (Absolutely converted)




(a) Synchronous 9-Pulse




(b) Synchronous 5-Pulse




(c) Synchronous 1-Pulse

Fig. 5 Synchronous PWM signal generation method.

The above equation (1) is derived under the condition that the voltage command (phase voltage) amplitude calculated by current control and the fundamental wave (phase voltage) amplitude extracted by Fourier transforming the PWM voltage waveform of 5 synchronous pulses are equal. Refer to the appendix for the derivation process.

Since the practical range of the width x in 5 synchronous pulses is about 0 to 6 [deg], the approximation of sinΔθ≈Δθ is applied to equation (1), and the width x is calculated by the following equation.

$$x \fallingdotseq \frac{1}{2} - \frac{\pi}{2\sqrt{6}}\frac{V_1^*}{E_{dc}} \tag{3}$$

When comparing with the triangular wave carrier, the width x is converted into the modulation factor amplitude Vx of the specific adjustment section by the following equation. (In terms of software implementation, the following equation is further converted to a modulation factor λ and a PWM timer value.)

$$V_x = -\frac{E_{dc}}{20_{[\mathrm{deg}]}} \times x_{[\mathrm{deg}]} + \frac{E_{dc}}{2} \tag{4}$$

### 3.2.3. Synchronous 1 pulse (Square wave)

Synchronous 1-pulse is realized by setting the width x to 0 [deg] (maximizing the modulation coefficient of the specific adjustment section) in the synchronous 5-pulse algorithm (Equation (4)).

As a result, the same triangular wave carrier comparator as other PWM signal generation (asynchronous PWM, synchronous 9,5 pulse) can be used to generate a synchronous 1-pulse signal that ensures the symmetry of the output voltage waveform.

Further, since the above-mentioned PWM control makes the relationship between the modulation factor command value and the actual inverter output voltage proportional (as shown in Figure 6), it is possible to avoid deterioration of control performance due to PWM control.

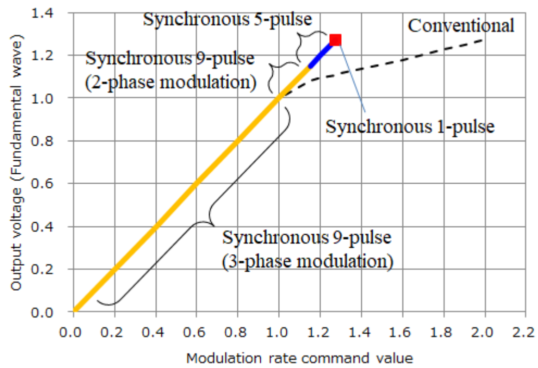



Fig. 6 Relationship between modulation rate command value and actual output voltage by proposed method.

### 3.2.4. How to apply PWM control

Figure 7 shows the application area of the PWM control methods for the inverter output frequency (proportional to the motor rotation speed) and the inverter output voltage (line to line voltage).

As shown in Figure 7, the output voltage of synchronous 1-pulse increases 1.1 times with respect to the maximum voltage of asynchronous PWM. If the PWM control method is changed instantly from asynchronous PWM to synchronous 1-pulse, there is a risk of overcurrent due to a sudden change in output voltage. Therefore, the intermediate voltage from asynchronous PWM to synchronous 1-pulse is interpolated by synchronous 9 pulses and synchronous 5 pulses, and the output voltage is continuously changed to shift to synchronous 1-pulse.

In addition, at the time of 1-pulse (voltage saturation), the load angle is automatically controlled by the weakening magnetic flux control. Therefore, it is not necessary to switch the torque control method, such as load angle control because it is a synchronous 1-pulse, and vector control for other cases.

For this reason, the proposed method is characterized by vector control under all operating conditions regardless of asynchronous PWM or synchronous 1-pulse.

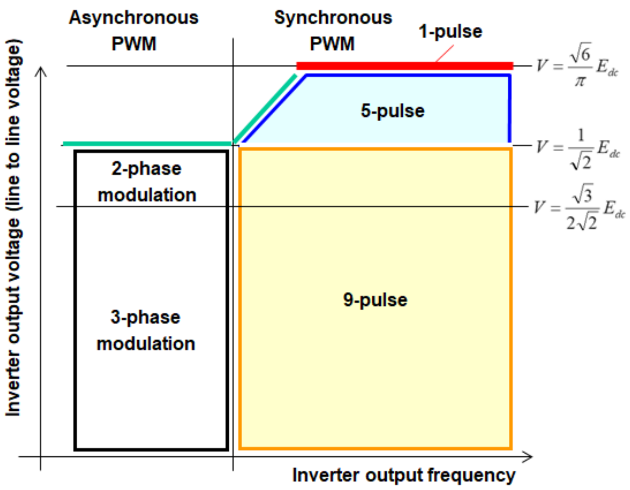



Fig. 7 Application area of PWM control methods.

## 4. EXPERIMENTAL RESULTS

The effectiveness of the proposed PWM control method will be confirmed by experiments using a high-speed rotary motor (PMSM). The specifications of the experimental system are shown in Table 1.

Table. 1 The specifications of the experimental system.

| items | value |
|---|---|
| Number of poles | 8 [poles] |
| Maximum power | 63 [kW] |
| Maximum torque | 150 [Nm] |
| Maximum rotation speed | 18,000 [min$^{-1}$] |
| DC link voltage | 300 [Vdc] |
| Maximum current of inverter | 320 [Arms] |
| Carrier frequency (Asynchronous PWM) | 7 [kHz] |

### 4.1. Characteristics of PWM method transition

Fig. 8 shows the inverter output voltage and the inverter output current waveform when the torque command value is changed from 20 to 0 [Nm] at a motor rotation speed of 18000 [min$^{-1}$].

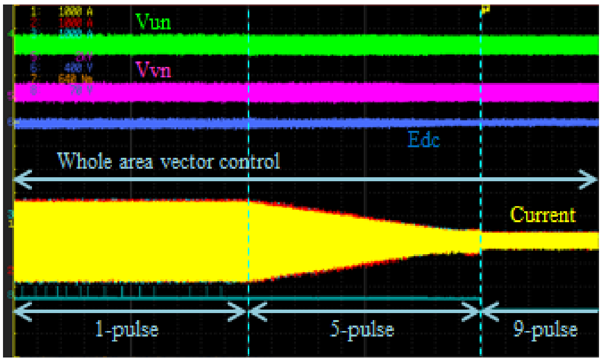
When operated as described above, the PWM control method is automatically switched in the order of synchronous 1-pulse, synchronous 5-pulse, and synchronous 9-pulse.

It was confirmed that stable switching is possible without causing current jumping even when the PWM method changes.

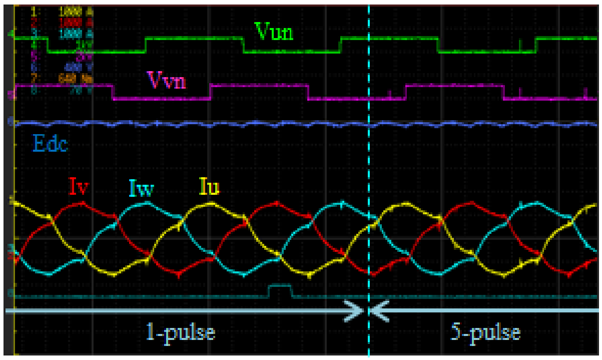
### 4.2. Characteristics of inverter efficiency

Fig. 9 shows a comparison of the proposed synchronous 1-pulse and asynchronous PWM with respect to inverter loss, motor loss, and system efficiency.

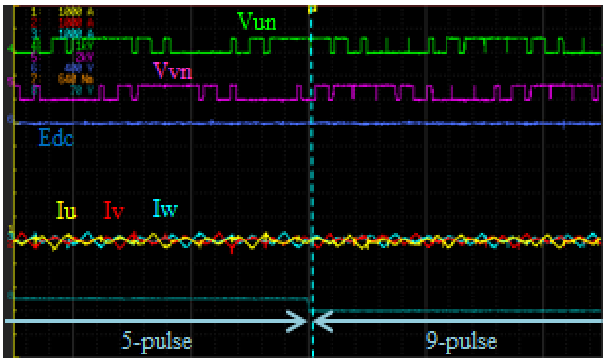
It was confirmed that the inverter loss during the proposed synchronous 1-pulse control was reduced to 42% compared to the asynchronous PWM control, and the system efficiency could be improved by 1 point.




(a) Overall




(b) Synchronous 1 pulse ⇒ Synchronous 5 pulse




(c) Synchronous 5 pulse ⇒ Synchronous 9 pulse

Fig. 8 Application area of PWM control methods.

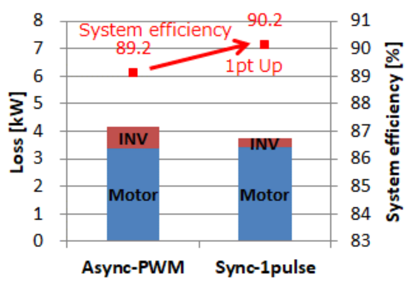



Fig. 9 Characteristics of loss and efficiency. (300Vdc, 18000rpm, 20Nm)

## 5. CONSIDERATION

In the general 1-pulse method, the mainstream method is to control the phase angle by torque feedback control while fixing the inverter output to 1-pulse.

In this section, we summarize the differences (advantages and disadvantages) between the 1-pulse fixed method and the proposed method in Table 2, and consider issues that should be improved in the proposed method.

### 5.1. 1-pulse fixed method

The 1-pulse fixed method can be minimized inverter switching loss by fixing 1-pulse.

On the other hand, when switching between synchronous 1-pulse and asynchronous PWM, it is necessary to switch the control method (eg, switch between torque feedback control and current feedback control). Therefore, it is necessary to take measures to prevent torque (current) shocks at the switching point of the control method (eg, tightening the integral term preset value of current control).

### 5.2. Proposed method

The proposed method is no need to switch control method for motor drive (overall current feedback control).

On the other hand, when the inverter output voltage is saturated, since it operates near the boundary between 1-pulse and 5- pulses the number of switching times (switching loss) increases compared to the 1-pulse fixed method.

### 5.3. Improvements of the proposed method

From the above, the proposed method has room for further efficiency improvement under operating conditions around 1-pulse.

In the future, we will study measures to reduce the number of switching operations in the operating region where 1-pulse of voltage is required for further efficiency improvement.

## 6. CONCLUSION

In this paper, we proposed a PWM control method that improves the voltage utilization rate of the inverter. In addition, compared with the 1-pulse fixed method, the points to be improved in the proposed method were considered.

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Table. 2 Advantages and disadvantages of the methods.

| Methods | Advantages | Disadvantages |
|---|---|---|
| 1-pulse fixed method | Inverter switching loss can be minimized by fixing 1 pulse. | It is necessary to switch the control method (eg, torque feedback control and current feedback control). |
| Proposed method | No need to switch control method (overall current feedback control). | The number of switching times increases compared to the 1-pulse fixed method. |

## APPENDIX

Figure 10 shows the relationship between the proposed synchronous 5-pulse voltage command, triangular wave carrier, and PWM output voltage.

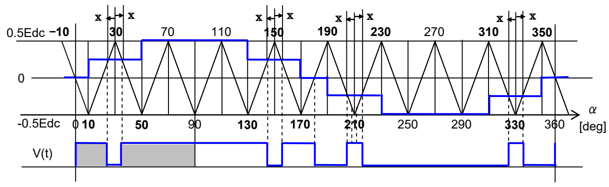


Fig. 10 Characteristics of loss and efficiency.

The fundamental wave component of the PWM output voltage V (t) is calculated using the Fourier series as follows.

$$V(t) = \sum \{a_n \cos(n\omega t) + b_n \sin(n\omega t)\}$$

$$a_n = \frac{1}{\pi}\int V(t)\cos(n\omega t)d\omega t$$

$$b_n = \frac{1}{\pi}\int V(t)\sin(n\omega t)d\omega t$$

When the voltage waveform is symmetric every 90 [deg], only the sin component appears, so it becomes as follows.

$$a_n = 0$$

$$b_n = \frac{4}{\pi}\int V(t)\sin(n\omega t)d\omega t$$

The solution for the fundamental wave component b1 is as follows.

$$V_1^* \times \sqrt{\frac{2}{3}} = \frac{4}{\pi}\left\{\int_0^{\frac{\pi}{6}-x}\left(\frac{E_{dc}}{2}\right)\sin\theta d\theta + \int_{\frac{\pi}{6}-x}^{\frac{\pi}{6}+x}\left(-\frac{E_{dc}}{2}\right)\sin\theta d\theta + \int_{\frac{\pi}{6}+x}^{\frac{\pi}{2}}\left(\frac{E_{dc}}{2}\right)\sin\theta d\theta\right\}$$

$$= \frac{2E_{dc}}{\pi}\left\{-\cos\left(\frac{\pi}{6}-x\right)+\cos(0)+\cos\left(\frac{\pi}{6}+x\right)-\cos\left(\frac{\pi}{6}-x\right)-\cos\left(\frac{\pi}{2}\right)+\cos\left(\frac{\pi}{6}+x\right)\right\}$$

$$= \frac{2E_{dc}}{\pi}(1-2\sin x)$$

$$\sin x = \frac{1}{2}\left(1-\frac{\pi}{\sqrt{6}}\frac{V_1^*}{E_{dc}}\right)$$

$$x = \sin^{-1}\left(\frac{1}{2}-\frac{\pi}{2\sqrt{6}}\frac{V_1^*}{E_{dc}}\right)$$