A novel modulation method for three-phase inverter with pausable switching during arbitrary periods in an arbitrary phase

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***Abstract*—This paper proposes a novel modulation method for three-phase inverters used in interior permanent magnet synchronous motor (IPMSM) drives. The method can pause the switching during arbitrary periods in an arbitrary phase by changing zero voltage vector ratio, unlike conventional variable switching pause period PWM, which can only pause the switching of one phase while the modulation waveforms of the other two phases are uniquely determined. This paper shows through simulation that the proposed method can pause the switching of arbitrary phases during arbitrary periods. The effectiveness of the proposed method is also demonstrated in an experiment with actual equipment. The inverter efficiency of the proposed method improved by 3.4 percentage points, while the motor efficiency worsened by 0.43 percentage points compared to SVPWM.**

***Index Terms*—modulation method, motor drive, three-phase inverter, switching loss.**

I. Introduction

Three-phase AC motors are used as traction motors in many commercial EVs (electric vehicles). They are driven by a three-phase inverter, as shown in Fig. 1. Motor drive systems for EVs require compact, high efficiency, durableness, and low acoustic noise, which have led to intensive research on improving the performance of three-phase inverters. There are various pulses with modulation (PWM) methods exist, such as space vector PWM (SVPWM)[1] and discontinuous PWM (DPWM)[2]. It is known that the characteristics such as switching loss, common-mode noise and harmonic component distribution in three-phase current differ depending on the modulation method[3]–[5]. Among them, DPWM is known to reduce the number of switchings by about two-thirds compared to SVPWM, thereby reducing switching losses, improving inverter efficiency, and suppressing heat generation in switching devices.

Moreover, depending on the physical arrangement inside the power module, unbalance of the three-phase current due to wiring geometry, and the operating conditions of the motor, the heat generated by the switches may be unevenly distributed in some parts of the power module[6]–[8]. For example, in the motor drive system of an EV, if the vehicle is stopped for long periods by pressing down on the accelerator instead of the foot brake to generate torque against gravity on an uphill, some switches generate excessive heat. Therefore, it is necessary to suppress the heat generated by switches in the hotter phases after starting the vehicle. Conventional DPWM[2] is expected to reduce the heat generated by the switches by reducing the number of switchings. However, in this case, the pause period of switching is equal in all three phases regardless of the heat generation bias, which may result in uneven heat distribution. Therefore, this study examines the application of VSPPPWM (variable switching pause period PWM)[8], which has been proposed to equalize unbalanced losses caused by unbalanced current paths in a three-phase inverter. In reference [8], a modulation method is proposed to equalize the temperature of switching devices in a power module by varying the pause period of switching. The method extends the pause period for upper and lower switching devices of a specific phase in the modulation waveform of DPWM by θ [rad], as shown in Fig. 2, while shortening the pause period of switching for the other phases accordingly. However, this method allows for adjusting the pause period of switching for only one phase, and the pause period of switchings for the other phases cannot be independently determined. Additionally, the pause period of switching is equal for the upper and lower switches, so there is no flexibility in the pause period of switching in the same phase.

This paper proposes a novel VSPPPWM method that can pause the switching of arbitrary phases during arbitrary periods. The proposed method can also arbitrarily determine the pause period of switching the upper and lower switches in the same phase, which provides a more flexible method. In addition, the conventional method of determining the offset voltage of the modulation wave complicates the generation of the modulation wave due to mutual dependence between the pause

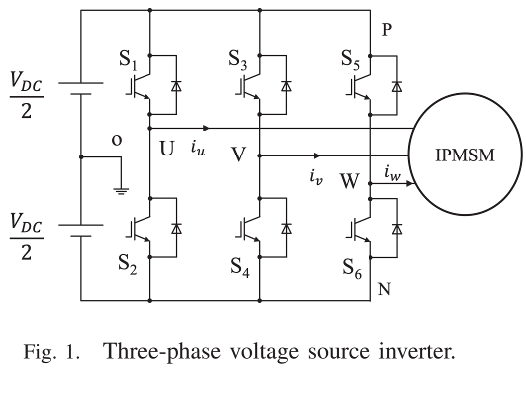


Fig. 1. Three-phase voltage source inverter.

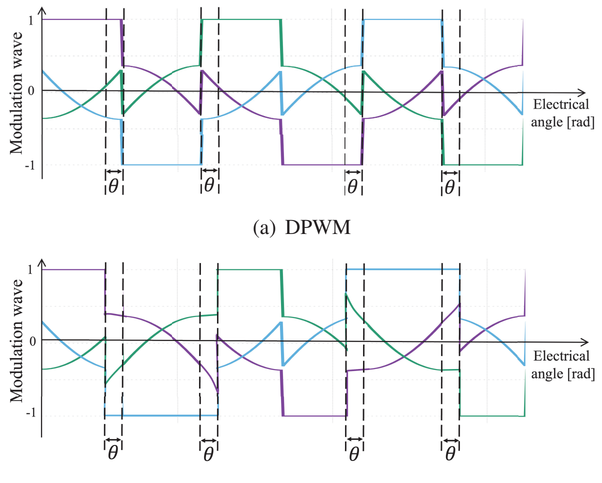
periods in each phase. The proposed method uses VZVRPWM (variable zero voltage ratio PWM)[9] to generate a modulation waveform by determining the ratio of zero voltage vectors to enable arbitrary switching pauses within a limited range. This paper demonstrates that the proposed method can pause the switching of arbitrary phases during arbitrary periods within a limited range through simulation. The effectiveness of the proposed method is experimentally verified using a test motor as an IPMSM (interior permanent magnet synchronous motor). Furthermore, this paper experimentally discusses the effect of the proposed method on efficiency.

II. Proposed method

This chapter presents the principle of the proposed PWM method, in which switching of arbitrary phases can be paused during arbitrary periods. A block diagram of the modulation wave generator of the proposed method is shown in Fig. 3. The following sections show methods for generating the modulation wave from zero voltage vector ratio k_N, which is shown in “Calculation of duty ratio” block[9] and for determining zero voltage vector ratio such that arbitrary phases can pause during arbitrary periods, which is shown in “Determination of zero voltage vector ratio” block.

A. Calculation of duty ratio

This section shows the method for determining the modulation wave using VZVRPWM[9], which corresponds to “Calculation of duty ratio” block in Fig. 3. Fig. 4 shows the output voltage vector that outputs $\boldsymbol{v_e}$ in the $\alpha\beta$ axis. Reference



(a) DPWM

(b) VSPPPWM[8]

Fig. 2. Modulation waveforms of DPWM and VSPPPWM.

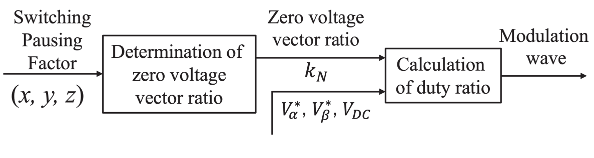


Fig. 3. Block diagram of modulation wave generator.

α and β voltages V_α, V_β [V] in sector 1 are given by the following equation.

$$\begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{2}{3}}V_{DC} \\ 0 \end{bmatrix} D_1 + \begin{bmatrix} \sqrt{\frac{1}{6}}V_{DC} \\ \sqrt{\frac{1}{2}}V_{DC} \end{bmatrix} D_2 \tag{1}$$

V_{DC} is the inverter input voltage, and D_1 and D_2 are the ratios of the active voltage vectors $\boldsymbol{v_{e1}}$ and $\boldsymbol{v_{e2}}$ in sector 1, respectively. Here, D_1 and D_2 are calculated using the following equations:

$$D_1 = \frac{\sqrt{3}V_\alpha - V_\beta}{\sqrt{2}V_{DC}}, \tag{2}$$

$$D_2 = \frac{\sqrt{2}V_\beta}{V_{DC}}. \tag{3}$$

A similar operation is performed for all sectors, yielding the results in Table I. Where the ratio of odd voltage vectors $\boldsymbol{V_1}$, $\boldsymbol{V_3}$, and $\boldsymbol{V_5}$ is D_{odd}, and the ratio of even voltage vectors $\boldsymbol{V_2}$, $\boldsymbol{V_4}$, and $\boldsymbol{V_6}$ is D_{even}. In addition, X, Y, and Z in Table I are shown in the following equation.

$$X = \frac{\sqrt{2}V_\beta}{V_{DC}} \tag{4}$$

$$Y = \frac{\sqrt{3}V_\alpha + V_\beta}{\sqrt{2}V_{DC}} \tag{5}$$

$$Z = \frac{\sqrt{3}V_\alpha - V_\beta}{\sqrt{2}V_{DC}} \tag{6}$$

Based on the above calculations and the zero voltage vectors $\boldsymbol{V_0}$ and $\boldsymbol{V_7}$, the synthetic output voltage vector $\boldsymbol{v_e}$ is shown by the following equation:

$$\boldsymbol{v_e} = \boldsymbol{v_{odd}} + \boldsymbol{v_{even}} + \boldsymbol{V_0} + \boldsymbol{V_7}, \tag{7}$$

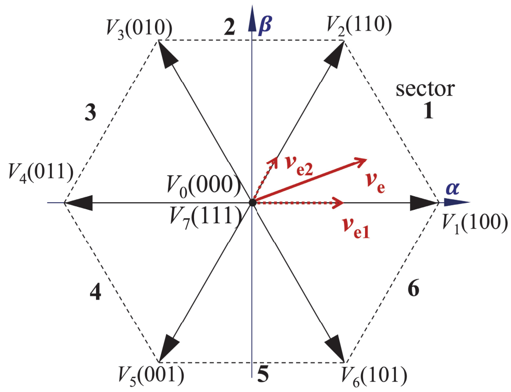


Fig. 4. Output voltage vector.

TABLE I
RATIO OF ACTIVE VOLTAGE VECTORS IN EACH SECTOR.

sector	1	2	3	4	5	6
D_{odd}	Z	$-Z$	X	$-X$	$-Y$	Y
D_{even}	X	Y	$-Y$	$-Z$	Z	$-X$

X, Y, and Z are defined in (4) to (6), respectively.

where the odd and even active voltage vectors are $\boldsymbol{v_{odd}}$ and $\boldsymbol{v_{even}}$, the duty ratios of $\boldsymbol{V_0}$ and $\boldsymbol{V_7}$ are D_0 and D_7, respectively. The switching cycle is as in Fig. 5. In this paper, the phases are defined as a, b, and c in order from the phase with the largest duty ratio. The duty ratios of the upper arm switches for each phase, D_a, D_b, and D_c, are calculated as follows from Fig. 5.

$$D_a = D_{odd} + D_{even} + D_7 \quad (8)$$

$$D_b = D_{even} + D_7 \quad (9)$$

$$D_c = D_7 \quad (10)$$

The ratios of D_0 and D_7 are flexible because $\boldsymbol{V_0}$ and $\boldsymbol{V_7}$ are zero voltage vectors. Here, by expressing zero voltage vector ratio k_N in sector N in the following equation, various modulation waveforms can be expressed using only the variable k_N[9].

$$k_N = \frac{D_7}{D_0 + D_7} \quad (11)$$

In this study, zero voltage vector ratio is constant within a sector. The duty cycle of each phase in VZVRPWM proposed in [9] is calculated as follows from (10), (11), and Fig. 5.

$$D_a = k_N + (1-k)D_{odd} + (1-k_N)D_{even} \quad (12)$$

$$D_b = k_N - k_N D_{odd} + (1-k_N)D_{even} \quad (13)$$

$$D_c = k_N - k_N D_{odd} - k_N D_{even} \quad (14)$$

Equations (12) to (14) show that the modulation wave is uniquely decided by determining k_N. Furthermore, it is necessary to determine k_N such that arbitrary phases are paused during arbitrary periods. The method for determining k_N is shown in the next section. In this study, k_N is kept constant in a sector to simplify the theory. However, VZVRPWM can change zero voltage vector ratio within each switching cycle in the shortest possible time, so it is also possible to determine the pause period of switching in the finer period.

B. Determination of zero voltage vector ratio

This section describes "Determination of zero voltage vector ratio" block in Fig. 3. This block determines zero voltage vector ratio k_N for each sector such that arbitrary phases

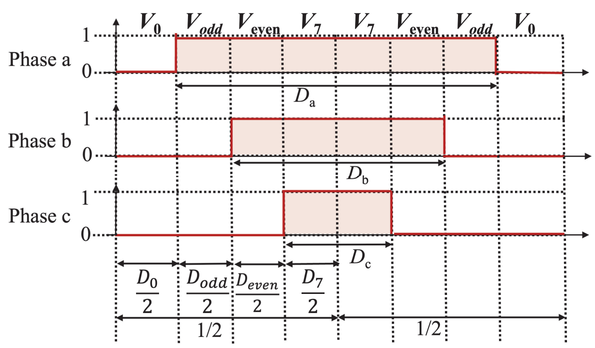


Fig. 5. Switching pattern in a carrier cycle.

are paused during arbitrary periods according to the following steps.

*Step 1 Determine switching pausing factor (**SPF**)*

Switching Pausing Factor (***SPF***) determines the pause period of each phase and is calculated using the following equation:

$$\boldsymbol{SPF} = (x, y, z), \quad (15)$$

where ***SPF*** components x, y, and z are the number of paused sectors per electrical angle cycle of u, v, and w phases, respectively. A larger value of ***SPF*** component means a longer paused period of switching. For example, if ***SPF*** is (4, 2, 0), the u-phase pauses four sectors, resulting in one-third of the number of switchings compared to SVPWM. The v-phase pauses two sectors, resulting in two-thirds of the number of switchings, while w-phase has the same number of switchings as SVPWM. In addition, ***SPF*** components have to meet the following conditions:

$$0 \leq x + y + z \leq 6, \quad (16)$$

$$0 \leq x, y, z \leq 4. \quad (17)$$

Equation (16) indicates that the sum of x, y, and z equals the number of sectors because ***SPF*** components are integers in this paper. Equation (17) shows that each phase can pause switchings at a maximum of four sectors. In other words, compared to SVPWM, the total number of switchings for the three phases is two-thirds as in DPWM; however, the proposed method can reduce it to one-third at most in one phase.

*Step 2 Select the paused sectors based on the largest **SPF** component*

It is not possible to pause switching in all sectors, and which sectors to pause is determined by the value of k_N according to Table II. In Table II, the symbol "*" indicates that switching cannot be paused in that sector. First, the paused sector of the phase corresponding to the largest ***SPF*** component is selected based on Table II. The number of paused sectors equals the value of the corresponding ***SPF*** component. If there are multiple choices for the paused sectors, priority is given to the sectors that cannot pause switching (indicated by "*") in the phase corresponding to the second largest ***SPF*** component.

*Step 3 Select the paused sectors based on the second largest **SPF** component*

From Table II, select the paused sector of the phase corresponding to the second largest ***SPF*** component among the sectors not selected in Step 2. The number of paused sectors to select is the ***SPF*** component. If there are multiple choices for the paused sectors, priority is selected for the sectors that cannot pause switching (indicated by " * ") in the phase corresponding to the smallest ***SPF*** component.

*Step 4 Select the paused sectors based on the smallest **SPF** component*

From Table II, select the paused sector of the phase corresponding to the smallest ***SPF*** component among the sectors not selected in Steps 2 and 3.

Step 5 Determine zero voltage vector ratio k_N per sector

From Table II, determine the values of k_N based on the paused sector for each phase determined in Steps 1 to 4. From the above, k_N can be determined from any ***SPF***.

For example, the following shows the determination of k_N for ***SPF*** = (3, 2, 1). In Step 1, the ***SPF*** is determined. ***SPF*** = (3, 2, 1) are appropriate ***SPF*** components because it satisfies (16) and (17). In Step 2, select the paused sectors based on the largest ***SPF*** component. Since ***SPF*** = (3, 2, 1), three paused sectors for u-phase are determined in Step 2. From Table II, three paused sectors must be selected from sectors 1, 3, 4, and 6. Here, v-phase must be selected from unpaused sectors 1 and 4 because the second largest ***SPF*** component is corresponding v-phase. Therefore, the paused sectors for u-phase are preferentially 1 and 4. From the above, the paused sectors of u-phase are either 1, 3, 4, or 1, 4, 6. In this example, sectors 1, 3, and 4 are used since they are valid in either case. That is, select the one indicated with "○" for u-phase in sectors 1, 3, and 4. Next, in Step 3, select the paused sectors based on the second largest ***SPF*** component. Since ***SPF*** = (3, 2, 1), two paused sectors for v-phase are determined. Then u-phase paused sectors were determined to be 1, 3, and 4 in Step 2; two paused sectors for v-phase need to be selected from sectors 2, 5, and 6 based on Table II. Here, sectors 3 and 6 correspond to the smallest ***SPF*** component and cannot pause the switching for w-phase. Therefore, the paused sectors for v-phase are preferentially 3 and 6. From the above, the paused sectors of v-phase are 2, 6, or 5, 6. In this example, sectors 5 and 6 are used since they are valid in either case. In Step 4, select the paused sectors based on the smallest ***SPF*** component. Since ***SPF*** = (3, 2, 1), one paused sector for w-phase is determined in Step 4. Since u-phase and v-phase paused sectors were determined to be 1, 3, 4, 5, and 6 in Steps 2 and 3, w-phase paused sector is 2 from Table II. Finally, determine zero voltage vector ratio k_N per sector in Step 5. From Steps 2 to 4, the paused sectors for u-phase were 1, 3, and 4, the paused sectors for v-phase were 5 and 6, and the paused sector for w-phase was 2. From Table II, k_N = (1, 0, 0, 0, 0, 0), where k_N is (k_1, k_2, k_3, k_4, k_5, k_6).

Therefore, in the system block diagram shown in Fig. 3, zero voltage vector ratio k_N can be determined in "Determination of zero voltage vector ratio" block from any ***SPF***. The modulation waves that pause the switching of arbitrary phases during arbitrary periods can be generated by inputting k_N determined in "Determination of zero voltage vector ratio" block to "Calculation of duty ratio" block.

TABLE II
THE VALUE OF k_N TO PAUSE SWITCHING OF THE SELECTED PHASE IN EACH SECTOR.

sector	1		2		3		4		5		6	
u-phase		○	*		○		○		*			○
v-phase	*			○		○	*		○		○	
w-phase	○		○		*			○		○	*	
k_N	0	1	0	1	0	1	0	1	0	1	0	1

* indicates that pause is impossible.
○ indicates that switching is pausable.

III. SIMULATION

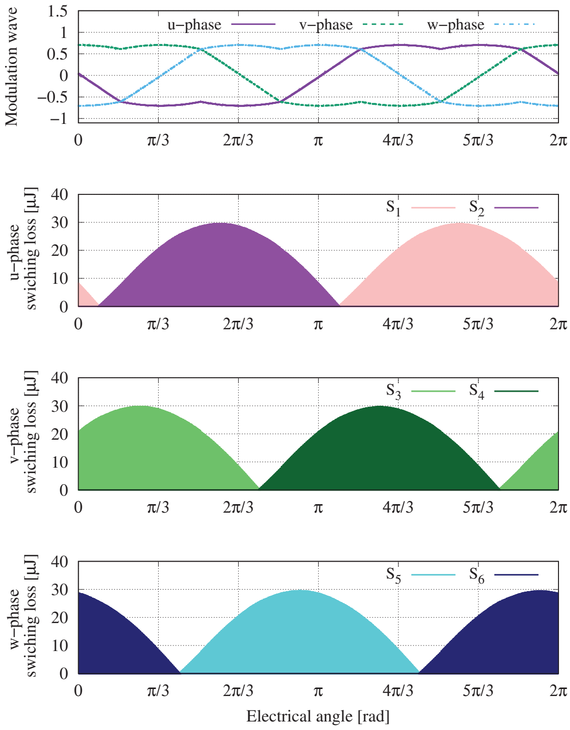
This chapter shows that the proposed method can pause the switching of arbitrary phases during arbitrary periods through co-simulations in *MATLAB/Simulink* and *PLECS*. In this study, simulations were performed using k_N determined from ***SPF***, as shown in Table III. The main circuit of the simulation consists of a battery, inverter, and IPMSM, as shown in Fig. 1. The motor parameters of the IPMSM in the simulation are shown in Table IV. The DC-link voltage V_{DC} = 100 V, and the machine angular velocity ω_m = 100 rad/sec. The motor was controlled with i_d = 0 control and a torque command value T_{ref} = 1 Nm. The IGBT library *FS50R06W1E3_B11_igbt* was used to analyze switching losses. Fig. 6 shows the modulation waves and switching losses of the conventional methods, SVPWM[1] and DPWM[2], at one cycle of electrical angle. Fig. 7 shows the modulation waves and switching losses of the proposed method at ***SPF*** shown in Table III. In both figures, S_1 to S_6 represent the switches in Fig. 1. It can be confirmed from Fig. 6 that SVPWM has no pause period of switching in the modulation wave. In addition, it can be confirmed that DPWM has a period of -1 in the modulation wave, resulting in the switching of the three phases being equally paused at the lower switches. Fig. 7 shows that the modulation wave of the proposed method is not equal in the three phases for the period of -1 or 1 (pause period of switching) when compared to Fig. 6(b). Switching losses of the specified switches can be reduced by the proposed method, as each phase can pause the period of switching based on ***SPF***. Therefore, the simulation results show that the proposed method can pause the switching of arbitrary phases during arbitrary periods. If the switching loss per electrical angle cycle of the SPWM is 100 %, the switching loss of DPWM is 58.44 %, showing that the switching loss is suppressed because the number of switchings is reduced to two-thirds. In contrast, the switching loss of the proposed

TABLE III
SWITCHING PAUSING FACTORS AND THE VALUES OF k_N USED IN THE SIMULATION.

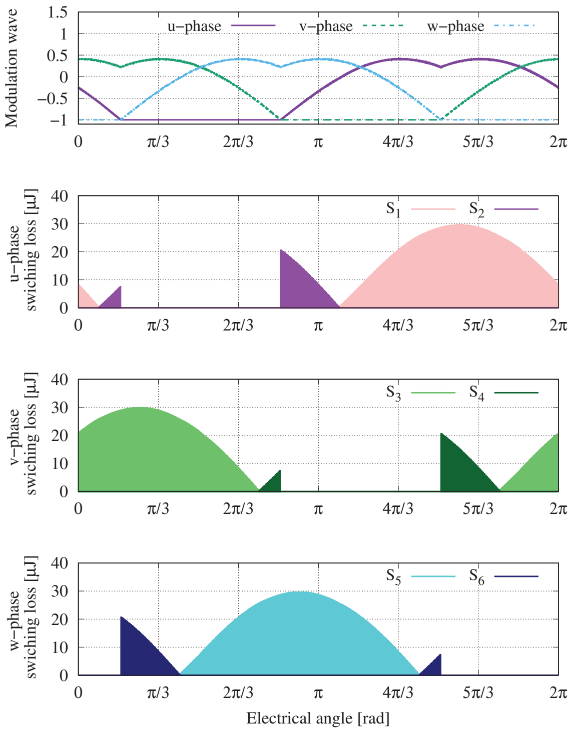
(x, y, z)	k_1	k_2	k_3	k_4	k_5	k_6
(4, 2, 0)	1	1	0	0	0	1
(4, 1, 1)	1	1	0	0	1	1
(3, 3, 0)	1	1	0	0	0	0
(3, 2, 1)	1	0	0	0	0	0

TABLE IV
MOTOR PARAMETERS OF IPMSM IN SIMULATION.

Number of pole pairs	2
d-axis inductance L_d	11.2 mH
q-axis inductance L_q	28.0 mH
Permanent magnet flux linkagex ψ_a	0.188 Wb
Winding resistance R_a	0.352 Ω

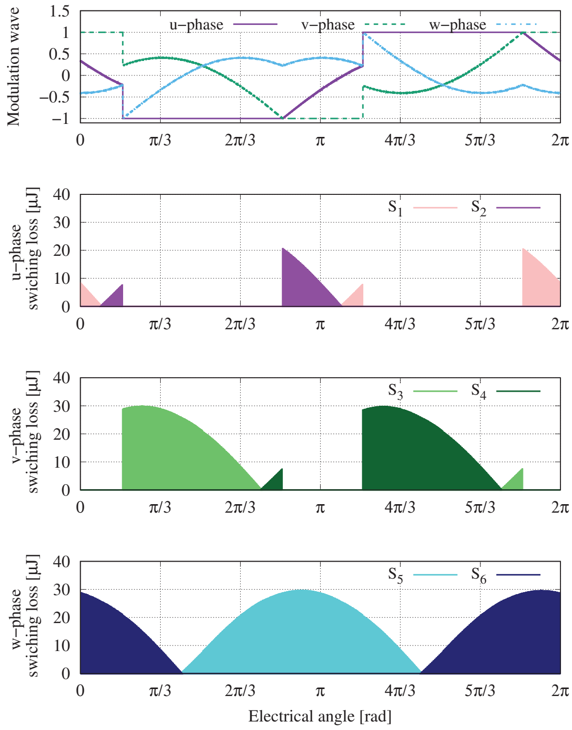


(a) SVPWM

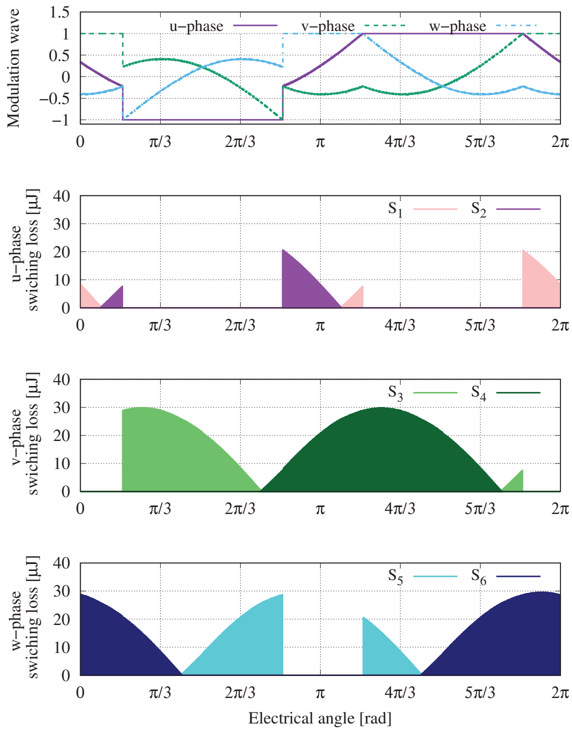


(b) DPWM

Fig. 6. Simulation results of the conventional method.

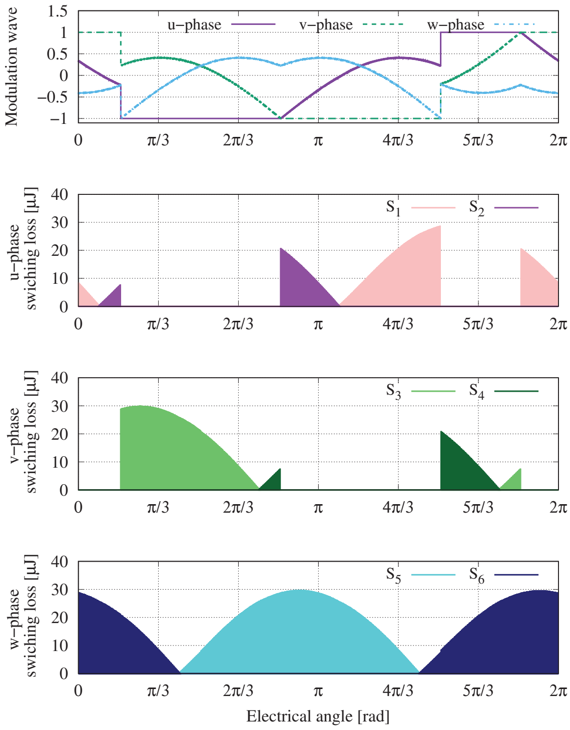


(a) ***SPF*** = (4, 2, 0)

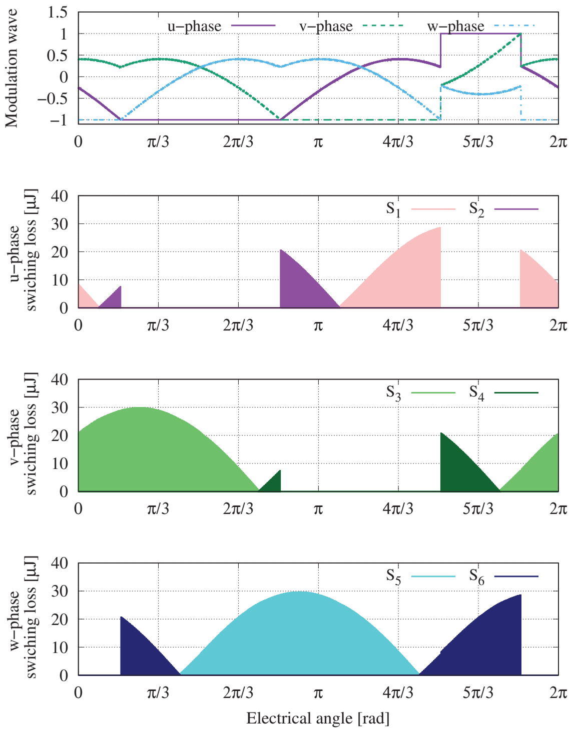


(b) ***SPF*** = (4, 1, 1)

Fig. 7. Simulation results of the proposed method.



(c) ***SPF*** = (3, 3, 0)



(d) ***SPF*** = (3, 2, 1)

Fig. 7. Simulation results of the proposed method (continued).

method is 56.37 $\sim$ 60.50 %. Also, if the number of switchings is the same, the switching loss depends on the phase difference between the current and voltage in each phase, and thus there is a difference of $\pm$2.06 % between the proposed method and DPWM.

IV. Experiment

In this chapter, experimental results show that the proposed method can pause the switching of arbitrary phases during arbitrary periods. The effects of the proposed method, SVPWM, and DPWM on the efficiency of the motor drive system are also discussed experimentally. Fig.8 shows the configuration of the experimental setup. An IPMSM used for a commercial hybrid electric vehicle with the motor parameters shown in Table V was used as the EUT, and the DC-link voltage V_{DC} of the inverter was supplied from a battery simulator and set to 360 V.

A generator is connected as the load to the test IPMSM to maintain a constant speed. The torque of the test IPMSM is controlled using *PE-Expert4*, a power electronics system controller manufactured by Myway Plus Corporation. *PE-Expert4* is equipped with a DSP *TMS320C6657*(1.25GHz) manufactured by Texas Instruments. The program that updates the voltage command every half carrier cycle is implemented in the DSP. As explained in the previous chapters, the controller generated a modulation wave that pauses the switching of arbitrary phases during arbitrary periods based on ***SPF***. Fig. 9 shows the experimental results of the modulation waves and three-phase currents when the dq axis current references $i_d^* =$ 0 A and i_q^* = 50 A, the motor speed is 1200 min^{-1}, and ***SPF*** is (4, 2, 0). It can be confirmed that the modulation waveform in Fig. 9 is such that the switching of four sectors in u-phase and two sectors in v-phase can be paused, similar to the modulation waveform in Fig. 7(a). Therefore, it is confirmed that the proposed method can generate a modulation waveform based on ***SPF*** in the experiment.

Next, a comparison of the efficiency of SVPWM, DPWM, and the proposed method is shown in Fig. 10. ***SPF*** in the proposed method is the value of k_N shown in Table III. The inverter, motor, and system efficiencies were calculated from the input and output power of the inverter and the motor IPMSM output power measured with *PW6001*, a power analyzer manufactured by HIOKI. As shown in Fig. 10, the efficiencies of the proposed method for all ***SPF***s and DPWM are similar. This is because the total number of switchings for the three phases is the same. The slight difference in efficiency can be considered to be due to the difference in switching losses caused by the phase difference between the current and voltage, as described in the previous section. The above results show that the proposed method has no disadvantage in efficiency compared to the conventional method of DPWM, which reduces the number of switchings, even though the modulation waves are different for each of the three phases.
Comparing SVPWM with the proposed method, the inverter efficiency improved by an average of 3.4 percentage points. This is due to the proposed method reducing the number of

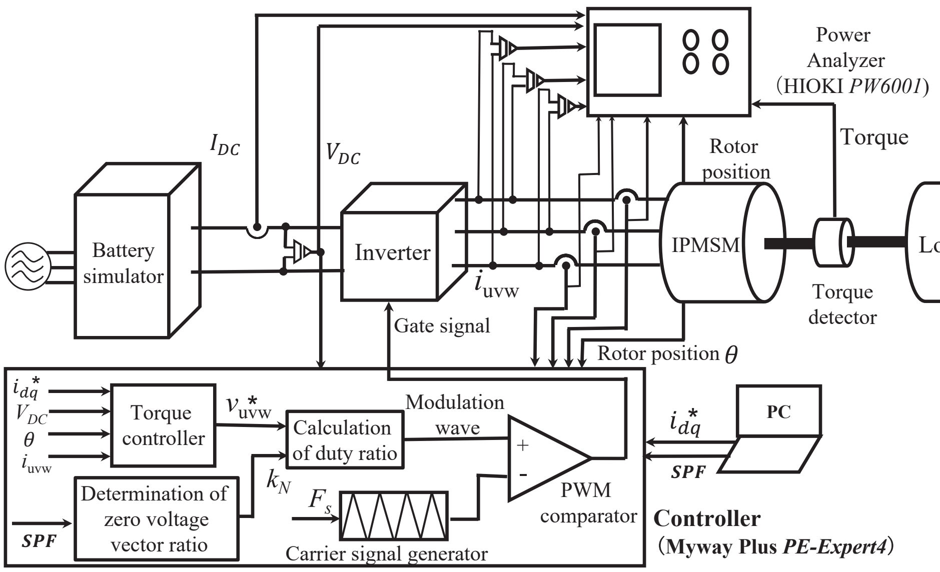


Fig. 8. Configuration of the experimental setup.

TABLE V
PARAMETERS OF THE EUT MOTOR.

Rated power	44.5 kW
Rated speed	5000 min^{-1}
Rated torque	170.0 Nm
Number of pole pairs	8
d-axis inductance L_d	428.9 μH
q-axis inductance L_q	497.7 μH
Permanent magnet flux linkage ψ_a	74.5 mWb
Winding resistance R_a	38.4 mΩ

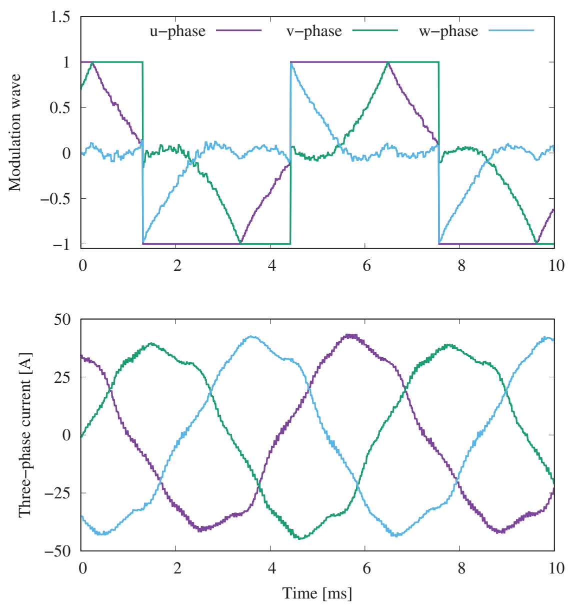


Fig. 9. Experimental results of modulation wave and three-phase current (***SPF*** is (4, 2, 1)).

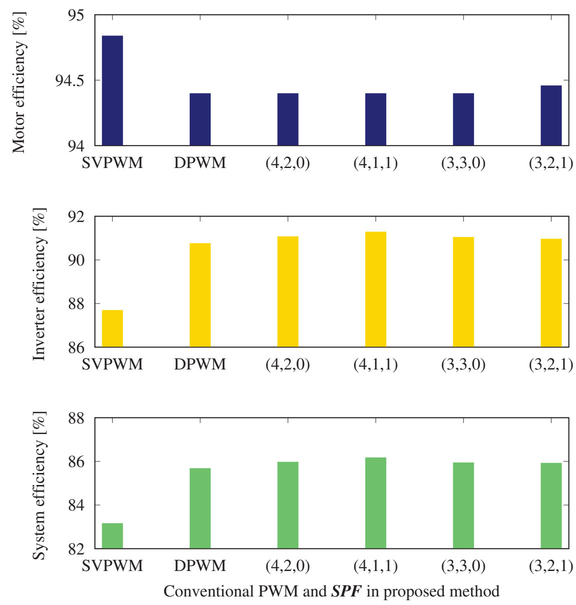


Fig. 10. Comparison of the efficiencies of SVPWM, DPWM and proposed method.

switchings by two-thirds compared to SVPWM. However, the motor efficiency of the proposed method and DPWM deteriorated by an average of 0.43 percentage points compared to SVPWM. Fig. 11 shows the THD (Total Harmonic Distortion) of the three-phase currents for each modulation method. As shown in Fig. 11, the THD of the other modulation methods is larger than that of SVPWM, and it is worse by an average of 6.27 percentage points. Therefore, it is considered that the motor efficiency deteriorated due to an increase in copper loss caused by the harmonics of the three-phase current.

The experimental results show that the proposed method is

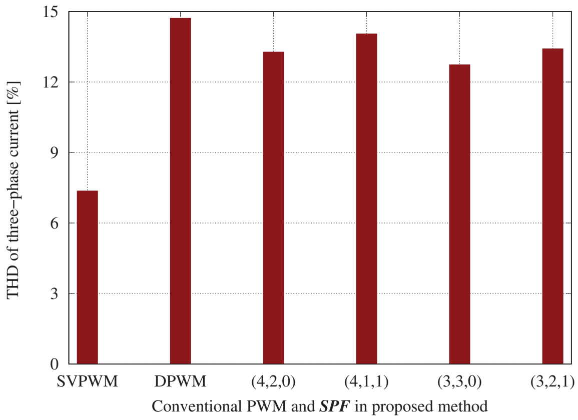


Fig. 11. THD of three-phase current for each modulation method.

effective in pausing the switching of arbitrary phases during arbitrary periods by generating a modulation wave based on ***SPF***. The efficiency of the proposed method is comparable to that of DPWM, which is a conventional method to reduce the number of switchings. This shows the proposed method has no disadvantage in efficiency, even if the modulation waves are different for the three phases.

V. Conclusion

This paper proposed a new VSPPPWM that could pause the switching of arbitrary phases during arbitrary periods within a limited range in a three-phase inverter. In the conventional VSPPPWM, the switching of one phase can be paused during arbitrary periods, while the modulation waveforms of the other two phases are uniquely determined. However, the proposed method can independently determine the pause period of switching of arbitrary phases by changing zero voltage vector ratio. This paper clarified by simulation that the proposed method could pause the switching of arbitrary phases during arbitrary periods. The experiments also demonstrated the effectiveness of the proposed method, and the effects of the proposed and conventional methods on efficiency were experimentally shown. The efficiency of the proposed method is comparable to that of DPWM, a conventional method that reduces the number of switchings. Therefore, it was shown that there was no disadvantage in efficiency when using a modulation method with different modulation waveforms for the three phases, such as the proposed method. However, the motor efficiency of the proposed method and DPWM is 0.43 percentage points worse than that of SVPWM. This is due to the increased THD of the three-phase current, which increases the copper loss.

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