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# An Improved Phase-Shifted DPWM Method for Reducing Switching Loss and Thermal Balancing in Cascaded H-Bridge Multilevel Inverter

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**ABSTRACT** This paper proposes an improved discontinuous pulse-width modulation (DPWM) method based on phase-shifted PWM (PS-PWM) for three-phase cascaded H-bridge (CHB) multilevel inverters. Due to the CHB multilevel inverters employ a large number of power semiconductor switches, they suffer from device failures because the switches are one of the major failure factors in a power electronic system. Therefore, the reliability and life-time of CHB multilevel inverters are mainly determined by the reliability of switches. The most failure of switches is occurred by its accumulated thermal stress which is generated by power losses including the conduction and switching loss. By applying the conventional DPWM, the life-time of switches can be extended because it reduces the switching loss. The conventional DPWM, however, still operates with high speed carrier frequency and it is not enough to reduce the switching loss of the CHB multilevel inverter with a large number of inverter cells. The proposed novel DPWM method provides the improved switching loss reduction through the different switching behaviors for each leg. Additionally, the rotation scheme promises even power distribution and life-time management among inverter cells in a CHB multilevel inverter. The simulation results and experimental results confirm the switching loss reduction and even power distribution abilities of the proposed modulation method.

**INDEX TERMS** Discontinuous pulse-width modulation, power losses, power distribution, cascaded H-bridge multilevel inverter, reliability of power conversion system.

## I. INTRODUCTION

Multilevel topologies are receiving increasing attention in industry due to various advantages such as capability for high voltage system, low harmonic distortion, and easy scalability [1]–[3]. Because of these characteristics, the multilevel inverters have been focused on high-power and medium-voltage applications [4]–[6]. However, the other characteristic of multilevel inverters is that a large number of devices are required such as passive components, gate drivers, and power semiconductor switches, etc. Especially, the failure of multilevel inverters more is occurred due to the increase in the switching devices and the reliability of multilevel inverters decreases. Many studies have been focused on the reliability improvement of multilevel inverters such as diagnosis and tolerance control of the switching device failures [7]–[9].

One of the most popular multilevel inverter is the cascaded H-bridge (CHB) multilevel inverter. The modular structure provides various modulation techniques and fault ride-through capability [10], [11]. The CHB multilevel inverter is composed of the series connected single-phase H-bridge cells that require four power semiconductor switches and isolated DC supplies in each of them. The switch is reported as a major failure factor in power conversion system [12]. Therefore, the study for reliability of switch is required for the high reliable and efficient CHB multilevel inverter. Many studies reported the failure mechanisms of power semiconductor switches are closely related to the accumulated thermal stress [13]–[17]. The major factor of the

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thermal stress is the power losses of the switches. Therefore, the power loss reduction can extend life-time of switch and it can improve reliability of CHB multilevel inverter [18]–[20].

The power loss of CHB multilevel inverter is related to its modulation method. The phase-shifted PWM (PS-PWM) is most popular carrier-based modulation technique, however, it generates great switching loss because all the switches are operated with the carrier frequency for a fundamental period of the output voltage. The easiest and effective solution is applying the conventional 60° DPWM. The DPWM scheme which is proposed in [15] applies clamping period to reduce the switching loss more. The clamping period, however, is assigned to a specific H-bridge leg and thus the power losses are not distributed evenly. In [19], a novel sinusoidal PWM (SPWM) was proposed and this method also adopted the clamping period. The reference signal for modulation is formed by mixing the sinusoidal wave and clamping period with rotation scheme. Therefore, it provides even power distribution among switching devices in an inverter cell. However, the method is obviously based on the SPWM which has no discontinuous period and it affords to reduce more switching loss.

This paper proposes an advanced DPWM scheme for the improved switching loss reduction than conventional discontinuous modulation schemes. The proposed modulation scheme adopts the conventional 60° DPWM and clamping state both in a fundamental period of the output voltage. Additionally, the rotation scheme is also proposed to distribute power loss evenly among the switching devices. This proposed DPWM scheme is the optimized carrier-based modulation in aspect of the power loss reduction and harmonic characteristic both. The proposed modulation scheme is compared with the other schemes and the effectiveness is highlighted with various simulation and experimental results.

## II. PRINCIPLE OF OPERATION IN THREE-PHASE CHB MULTILEVEL INVERTER

In the following, the principles of operation for CHB multilevel inverter and H-bridge cell are reviewed. Fig. 1 shows simplified topology of three-phase CHB multilevel inverter and configuration of H-bridge cell. Here, $V_{dc}$ denotes the isolated DC supply each cell, $v_{xN}$ denotes the output voltage of H-bridge cell that $x$-phase $N$-th, and $S_{xN1} \sim S_{xN4}$ denote the power semiconductor switches. The *Leg-L* consist of $S_{xN1}$, $S_{xN3}$, and the *Leg-R* consist of $S_{xN2}$, $S_{xN4}$.

### A. MODULATION METHOD FOR H-BRIDGE CELL

In single-phase H-bridge cell, the output voltage $v_{xN}$ is determined by either bipolar PWM method or unipolar PWM method. The two switches in same leg operate in a complementary manner that one switch is turn on when the other switch is turn off. The on-state of leg is that upper switch is turn on and lower switch is turn off. The off-state of leg is that upper switch is turn off and lower switch is turn on.

Fig. 2 shows a set of waveforms of the H-bridge cell for the modulation and different output voltage waveforms depending on the modulation methods; bipolar PWM method and unipolar PWM method. The bipolar PWM method

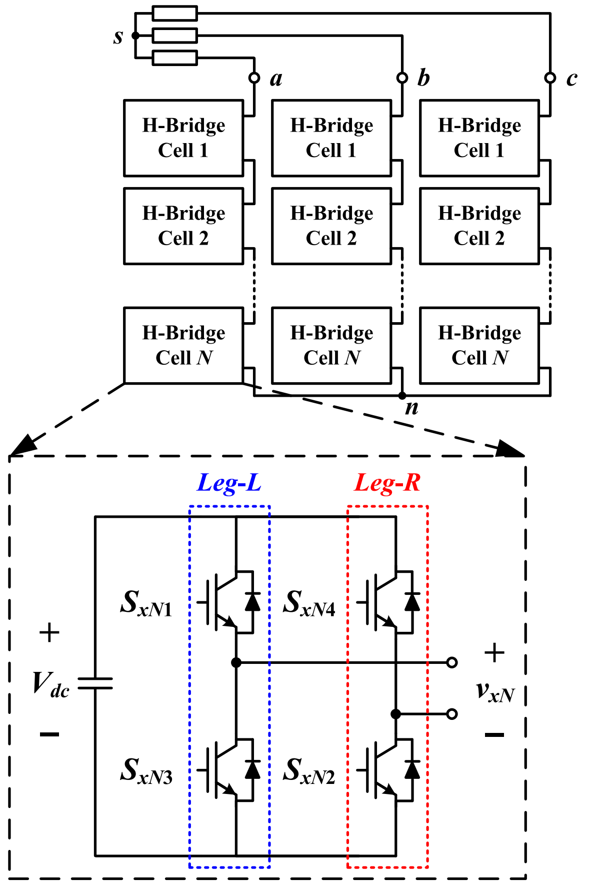



**FIGURE 1.** Topology of three-phase CHB multilevel inverter.

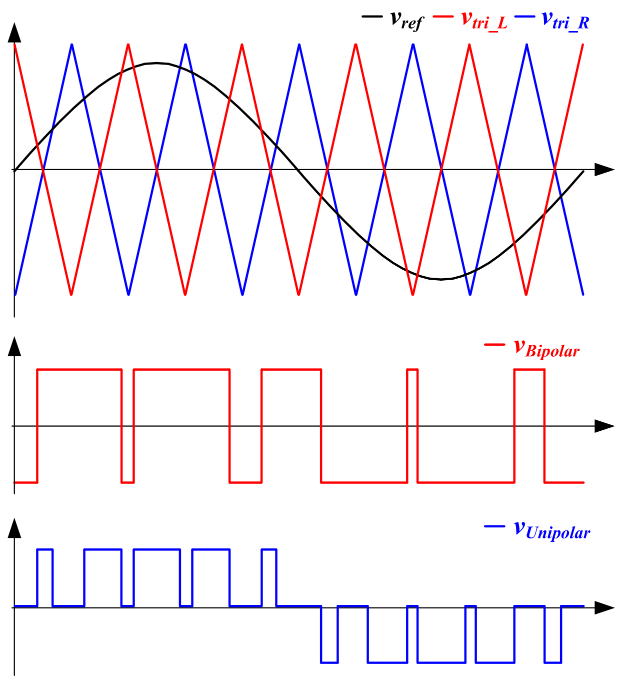



**FIGURE 2.** Waveforms depending on modulation method for single-phase H-bridge cell.

requires only one triangular carrier waveform that is either $v_{tri\_L}$ or $v_{tri\_R}$. The states of two legs are determined by comparing reference voltage $v_{ref}$ with triangular carrier waveform and these operate in a complementary manner. Therefore, the H-bridge cell with bipolar PWM method generates two output voltages ($V_{dc}$, $-V_{dc}$).

The unipolar PWM method is operated switches independently by two triangular carrier waveforms. The two triangular carrier waveforms are of the same magnitude and frequency, however there are a phase shift between waveforms given by 180°. The two waveforms are compared with a common reference voltage $v_{ref}$, generating two gating signals that determine state of each leg. As shown Fig. 2, the output voltage switches either between 0 and $V_{dc}$ during the period of positive $v_{ref}$ or between 0 and $-V_{dc}$ during the period of negative $v_{ref}$. The magnitude between output voltages is small compared with bipolar PWM method and therefore, the total harmonic distortion (THD) of output voltage reduces.

### B. MODULATION METHOD FOR CHB MULTILEVEL INVERTER

The proposed method in this paper is based on unipolar PWM method. Therefore, all legs of the CHB multilevel inverter require independent triangular carrier waveforms. The CHB multilevel inverter uses H-bridge cells connected in a series chain to produce alternating current (AC) voltages. Therefore, the number of output voltage levels is depending on the number of H-bridge cells as follows:

$$L = 2N + 1 \tag{1}$$

where $L$ denotes the number of output voltage levels and $N$ denotes the number of H-bridge cells per phase. The modulation method for CHB multilevel inverter determines some characteristics such as the number of switching operation, switching frequency, and period of either turn on or turn off. Therefore, the power losses that generated by switching operation are related to modulation method for CHB multilevel inverter.

The modulation method for CHB multilevel inverter is divided two modulation method: LS-PWM method and PS-PWM method. The LS-PWM method generates lower switching loss than PS-PWM method. In LS-PWM method, the switching frequency of CHB multilevel inverter is equal to the triangular carrier frequency, while the switching frequency of leg is unequal to it. Therefore, the legs in CHB multilevel inverter applied LS-PWM method are operated at the unequal switching frequency and conduction time and the power losses are generated unevenly each leg. Fig. 3 shows waveforms of PS-PWM method for 5-level CHB multilevel inverter. The PS-PWM method based on unipolar PWM method requires $(L - 1)$ triangular carrier waveforms for modulation in CHB multilevel inverter. All triangular carrier waveforms have the same frequency and the same peak-to-peak amplitude. However, there is a phase shift between any two adjacent waveforms and it is expressed in equation (2).

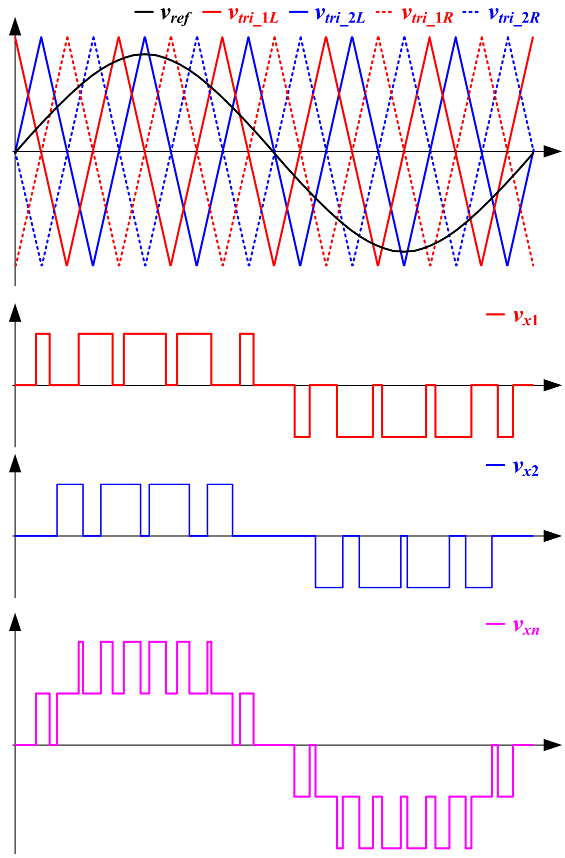



**FIGURE 3. Principle of PS-PWM method for 5-level CHB Multilevel inverter.**

$$\phi = \frac{2\pi}{L-1} = \frac{2\pi}{2N} \tag{2}$$

In PS-PWM method, the switching frequency of CHB multilevel inverter is related to the switching frequency of leg and it is expressed in equation (3).

$$f_{sw,CHB} = 2Nf_{sw,leg} = (L-1)f_{sw,leg} \tag{3}$$

Here, $f_{sw,CHB}$ denotes the switching frequency of CHB multilevel inverter and $f_{sw,leg}$ denotes switching frequency of leg. The output voltages of H-bridge cell produced by the PS-PWM method are identical except a small phase displacement among them. All legs in CHB multilevel inverter operate at the same switching frequency and conduction time. Therefore, the power losses applied PS-PWM method are generated evenly each leg.

## III. PROPOSED MODULATION METHOD FOR RELIABILITY AND EFFICIENCY IMPROVEMENT

This paper modifies PS-PWM method based on unipolar PWM method for improve reliability and efficiency in CHB multilevel inverter. As discussed above, the PS-PWM method generates evenly each leg, however, it is hard to applied to the CHB multilevel inverter with a large number of inverter cells due to its high switching loss. The PS-DPWM method provides the reduced switching loss characteristic by injecting the discontinuous modulation period. In the proposed DPWM method, the performance of switching loss reduction improves compared with the conventional PS-DPWM method. Additionally, the reliability issue that is generated by uneven switching loss among legs can be solved by the rotation scheme. The conventional PS-DPWM which is mentioned in this paper utilizes the 60° DPWM.

### A. CONVENTIONAL PS-DPWM METHOD

The major objective that using PS-DPWM method is to reduce the switching losses through injecting discontinuous modulation period. There are different types of DPWM methods depending on injected discontinuous modulation period and it determines the switching loss, characteristic of THD and etc. In this paper, all DPWM methods are based on 60° DPWM method which the discontinuous modulation period is 60°.

The switching operation of PS-DPWM method for three-phase CHB multilevel inverter is performed by modifying existing reference voltages that are expressed as

$$\begin{aligned} v_{ref,a} &= \left(V_{mag}/N\right)\sin\left(\theta\left(t\right)\right) \\ v_{ref,b} &= \left(V_{mag}/N\right)\sin\left(\theta\left(t\right)-\left(2\pi/3\right)\right) \\ v_{ref,c} &= \left(V_{mag}/N\right)\sin\left(\theta\left(t\right)+\left(2\pi/3\right)\right) \end{aligned} \tag{4}$$

where $V_{mag}$ denotes magnitude and $\theta$ denotes the angle of the reference voltages depending on time $t$. The modified reference voltage of PS-DPWM method that is expressed in equation (5) is calculated by adding equation (4), (6).

$$v_{DPWM,ref,x} = v_{ref,x} + v_{off} \quad (x = a, b, c) \tag{5}$$

$$v_{off} = \begin{cases} \dfrac{-V_{dc}}{2} - v_{\min} & (|v_{\max}| < |v_{\min}|) \\ \dfrac{V_{dc}}{2} - v_{\max} & (|v_{\max}| \geq |v_{\min}|) \end{cases} \tag{6}$$

In equation (6), $v_{max}$ and $v_{min}$ denote the maximum and minimum voltages of $v_{ref,x}$ ($x = a, b, c$), respectively. The states of legs are determined by comparing reference voltage of PS-DPWM method that is shown in Fig. 4. The discontinuous modulation period locates at positive and negative peak of reference voltage for 60° of the fundamental period.

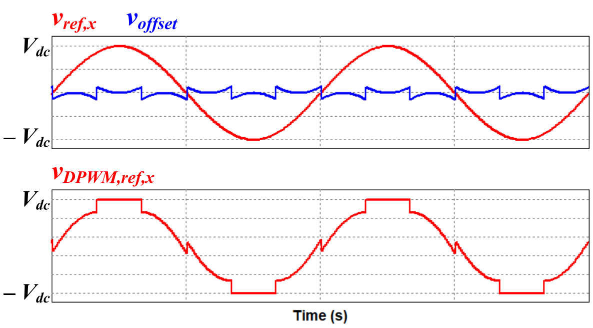



**FIGURE 4.** The waveforms of conventional PS-DPWM method.

### B. PROPOSED PS-CDPWM METHOD

In conventional PS-DPWM method, all leg of CHB multilevel inverter are switched high frequency switching operation except discontinuous modulation period. The proposed phase-shifted clamping DPWM (PS-CDPWM) method is reduced switching loss by injecting clamping period. The leg that injected clamping period performs switching operation at fundamental frequency of output voltage. The reference voltages for PS-CDPWM method are calculated by using $v_{clamp,off}$ that is expressed in equation (7).

$$v_{clamp,off} = \begin{cases} -V_{dc} - v_{DPWM,ref,x} & \left(v_{DPWM,ref,x} < 0\right) \\ V_{dc} - v_{DPWM,ref,x} & \left(v_{DPWM,ref,x} \geq 0\right) \end{cases} \tag{7}$$

In PS-CDPWM method, the reference voltages are expressed in equation (8), and the different reference voltages are applied each leg of same cell independently.

$$\begin{aligned} v_{ref,clamp} &= v_{DPWM,ref,x} + v_{clamp,off} \\ v_{ref,switch} &= v_{DPWM,ref,x} - v_{clamp,off} \end{aligned} \tag{8}$$

Here, $v_{ref,switch}$ is reference voltage that is switched high frequency switching operation and $v_{ref,clamp}$ is reference voltage that injected clamping period. The reference voltages waveforms of PS-CDPWM method are shown in Fig. 5.

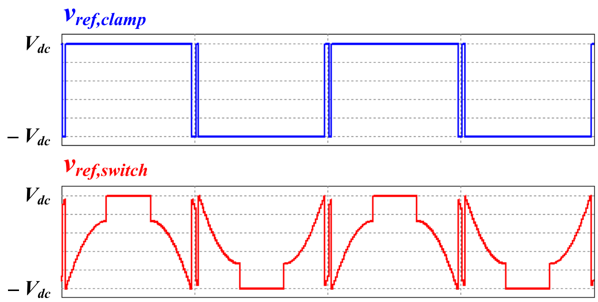
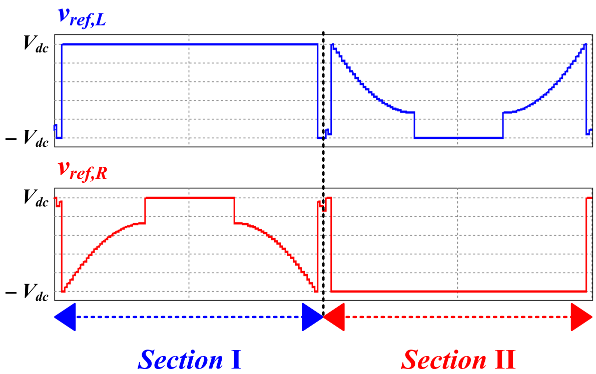



**FIGURE 5.** The reference voltages of PS-CDPWM method.

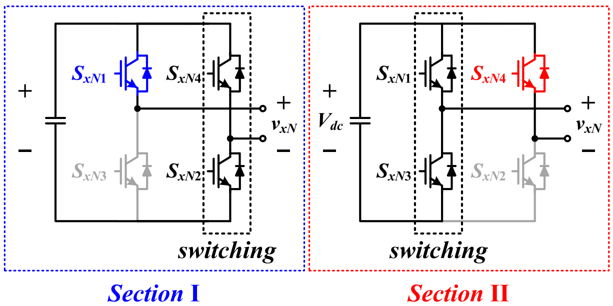
The leg that is applied $v_{ref,switch}$ perform high frequency switching operation that is frequency of triangular carrier waveform and its switching loss equal the conventional PS-DPWM method. In the leg that is applied $v_{ref,clamp}$, the switching frequency is fundamental frequency of output voltage and the switching loss reduces compared with the conventional PS-DPWM method. Therefore, the switching loss of PS-CDPWM method is generated unevenly each leg.

### C. ROTATION PS-CDPWM METHOD

The cause of major failure in power semiconductor switch is thermal stress and thermal stress is generated by power losses. Therefore, the uneven switching losses occur unbalancing life-time of power semiconductor switches, and it decreases reliability of CHB multilevel inverter. To evenly distribute the switching losses, the reference voltage that injected clamping period should distribute to each leg. The rotation PS-CDPWM method is applied rotate method to evenly distribute switching losses and thermal stress.




(a) The waveforms of reference voltages

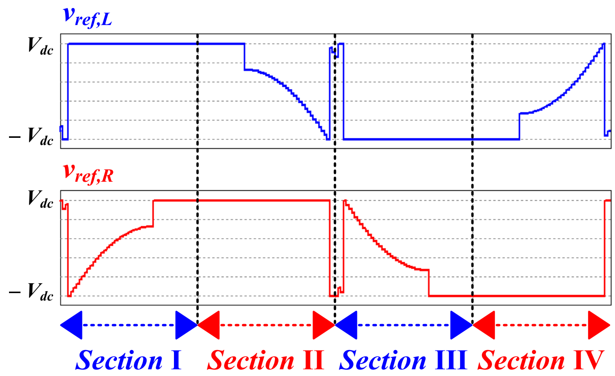



(b) Switch state of H-bridge cell

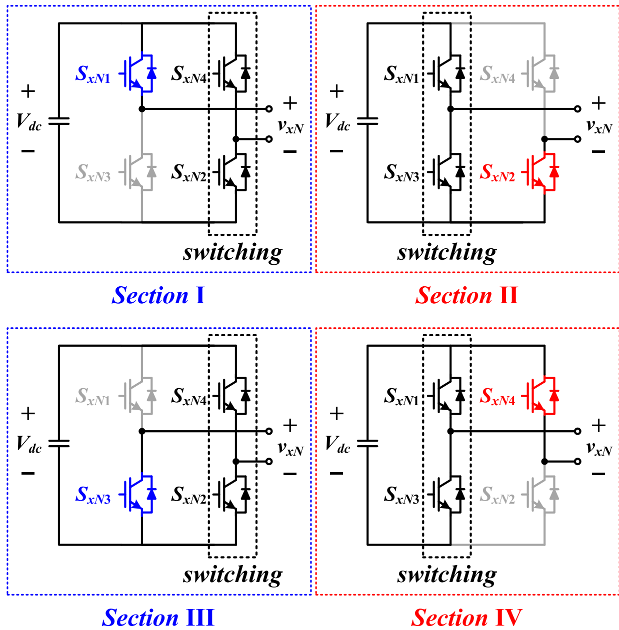
**FIGURE 6. The PS-CDPWM method with 1/2 rotation period.**

The purpose of rotate method is that evenly distribute switching loss to both leg and power semiconductor switches. Therefore, the rotate period should be decided considering switching state of power semiconductor switches. Fig. 6 shows the reference voltages each leg and switch state of H-bridge cell when rotate period is 1/2 of fundamental frequency. The switching loss of H-bridge cell are evenly distributed each leg by rotation PS-CDPWM method with 1/2 rotation period. However, the leg that is operated clamping switching generates switching loss unevenly each switches of same leg. As shown Fig. 6(a), each leg is on-state in section that operates clamping operation, therefore the loss is generated only upper switch. It causes uneven life-time each switch and generates reliability reduction of CHB multilevel inverter. Therefore, the 1/2 rotation period is inappropriate scheme to solve uneven switching loss and reliability reduction of CHB multilevel inverter.

In rotation PS-CDPWM method with 1/4 rotation period, the reference voltages each leg consists of four section during fundamental frequency as shown in Fig. 7(a). The clamping period of *Leg-L* with 1/4 rotation period is section I, III, and the state of leg are on-state, off-state, respectively. Therefore, the loss in clamping period of *Leg-L* is evenly




(a) The waveforms of reference voltages




(b) Switch state of H-bridge cell

**FIGURE 7. The PS-CDPWM method with 1/4 rotation period.**

distributed each switch. In clamping period of *Leg-R* such as section II, IV, the states of leg are alternated to distribute switching losses evenly. Therefore, the proposed rotation PS-CDPWM method can achieve the even loss distribution and the reference voltages for it are expressed in equation (9), (10).

$$v_{ref,L} = \begin{cases} v_{ref,clamp} & \begin{pmatrix} 0^\circ \le \theta < 90^\circ, \\ 180^\circ \le \theta < 270^\circ \end{pmatrix} \\ v_{ref,switch} & \begin{pmatrix} 90^\circ \le \theta < 180^\circ, \\ 270^\circ \le \theta < 360^\circ \end{pmatrix} \end{cases} \tag{9}$$

$$v_{ref,R} = \begin{cases} v_{ref,switch} & \begin{pmatrix} 0^\circ \le \theta < 90^\circ, \\ 180^\circ \le \theta < 270^\circ \end{pmatrix} \\ v_{ref,clamp} & \begin{pmatrix} 90^\circ \le \theta < 180^\circ, \\ 270^\circ \le \theta < 360^\circ \end{pmatrix} \end{cases} \tag{10}$$

### D. DOUBLE ROTATION PS-CDPWM METHOD CONSIDERING FOR POWER FACTOR

The power factor is phase difference between voltage and current, the phase of output current is lagged by load impedance and line impedance generally. In rotation PS-CDPWM method with 1/4 rotation period, each leg performs switching operation at different output current as shown in Fig. 8(a). Because the switching loss is determined by current when switching operation, the *Leg-L* switching loss that switches at peak of output current is generated more than *Leg-R*.

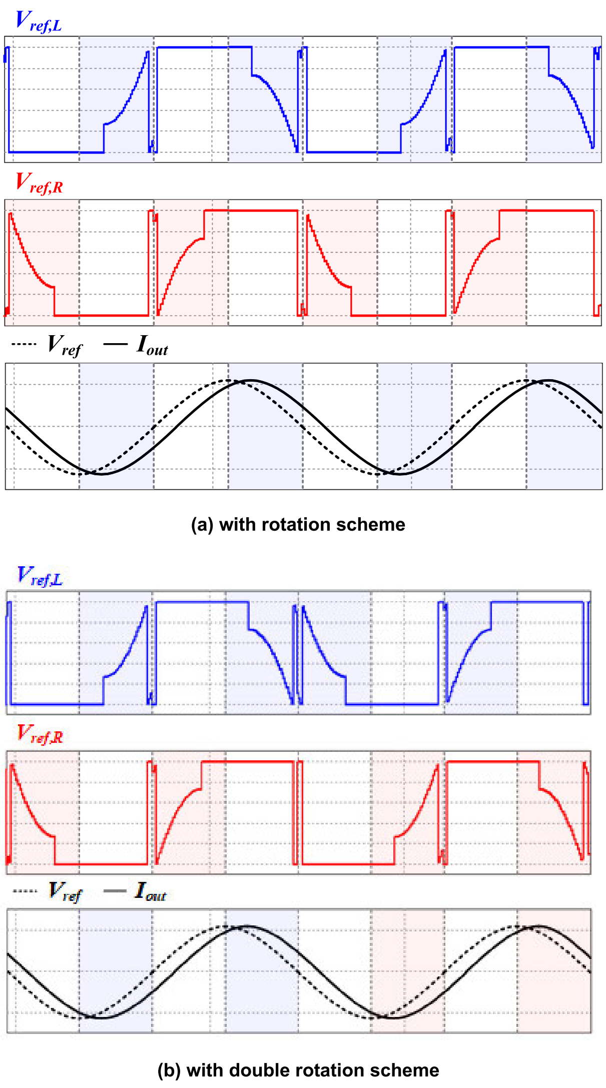



**FIGURE 8.** The PS-CDPWM method with double rotation scheme.

In order to distribute the generated switching loss evenly, the proposed rotation scheme additionally consider power factor. The double rotation scheme alternates the switching section each one cycle of the output current as shown in Fig. 8(b). Therefore, the leg that performs switching operation at peak value of output current is alternated by double rotation scheme. The proposed double rotation scheme distributes switching loss evenly regardless phase difference, therefore it can be applied to leading power factor.

The proposed PS-CDPWM is based on the 60° DPWM method. The basic concept of this modulation scheme is the combination of DPWM and additional clamping period. Therefore, the proposed method can be expanded with various DPWM method such as 30° DPWM. The one of the contribution of the proposed method is easy implementation by simple offset voltage design, however, the combination with 30° DPWM requires much greater computation burden to digital signal processor (DSP). Therefore, the 60° DPWM is suitable for this combined modulation scheme.

## IV. SIMULATION RESULTS

The simulation is conducted to verify the effectiveness of the proposed modulation method for CHB multilevel inverter. This simulation uses three-phase 5-level CHB multilevel inverter and its parameters are shown in Table 1. The three-type modulation method are simulated in this section by Powersim (PSIM) simulation tool.

**TABLE 1.** Simulation parameters.

| PARAMETER | Values |
|---|---|
| The number of H-bridge cell per phase, $N$ | 2 ea |
| The level of output voltage, $L$ | 5 ea |
| DC voltage of each cell, $V_{dc}$ | 400 V |
| Total DC voltage per phase | 800 V |
| Modulation index | 0.75 |
| Switching frequency, $f_{sw}$ | 10 kHz |
| Fundamental frequency of output voltage | 60 Hz |
| Load resistance, $R$ / Filter inductance, $L$ | 6 Ω / 2 mH |

Fig. 9 is simulation results of the conventional PS-DPWM method and shows the overall performance of the conventional PS-DPWM method. The gating signal such as $S_{a11}$, $S_{a12}$ show adjected discontinuous period to peak of output current. The discontinuous period reduces the number of switching operation and switching loss. However, the high frequency switching operation that generates high switching loss is performed except discontinuous period in conventional PS-DPWM method. In Fig. 10, the simulation results show performance of PS-CDPWM method that reduces switching loss compared with conventional PS-DPWM method. In PS-CDPWM method, the switching frequency of one leg is fundamental frequency of output voltage. Therefore, the generated switching loss reduce compared with conventional PS-DPWM method. To solve problem of unevenly switching loss each switch, the rotation scheme applies to PS-CDPWM method. As shown Fig. 11, the rotation PS-CDPWM method that applied rotation scheme distributes

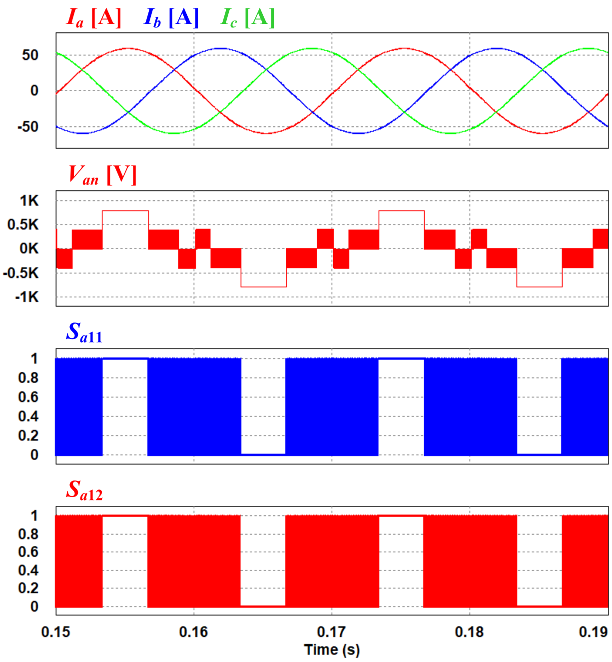



FIGURE 9. Simulation results of PS-DPWM method.

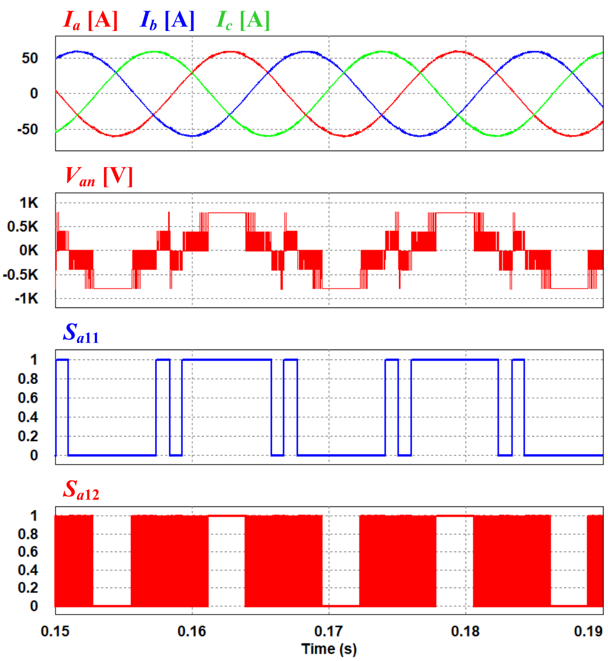



FIGURE 10. Simulation results of PS-CDPWM method.

switching loss evenly and it maintain performance compared to PS-CDPWM method.

Fig. 12 shows comparison of THD depending on modulation method and the number of harmonics for calculating THD is 100 order. The PS-CDPWM method has high THD compared with conventional PS-DPWM method. Because the double rotation scheme does not impact the performance of output, the THD of double rotation PS-CDPWM

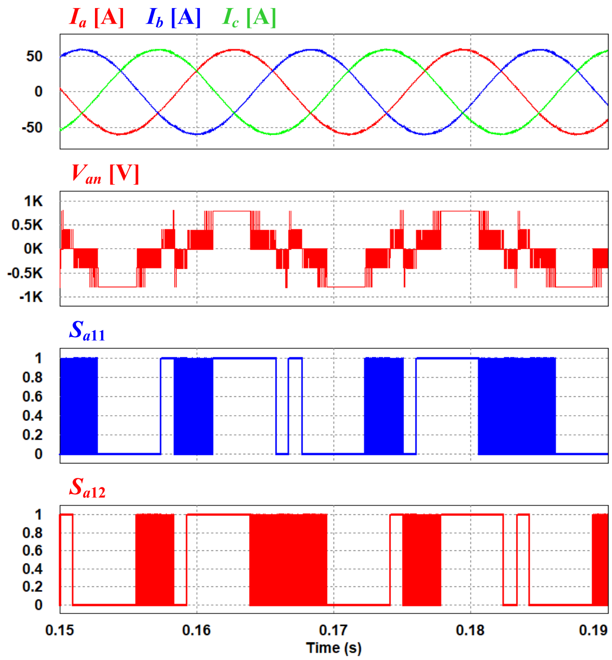



FIGURE 11. Simulation results of double rotation PS-CDPWM method with 1/4 rotation period.

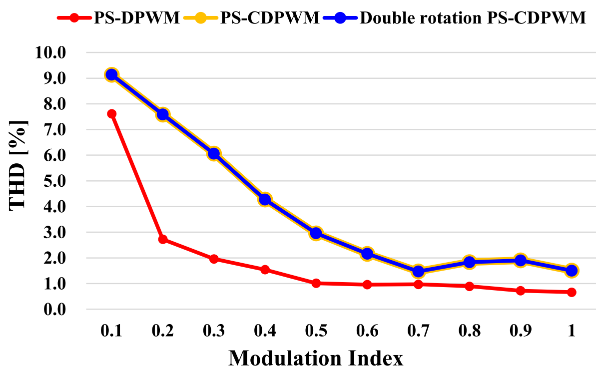



FIGURE 12. Comparison of THD depending on modulation method.

method is same THD of PS-CDPWM method. Owing to the PS-DPWM generates the higher equivalent switching frequency of output voltage, the harmonic characteristic is better than PS-CDPWM. Fig. 13, 14, 15 show frequency analysis results of the conventional PS-DPWM method, PS-CDPWM method, and double rotation PS-CDPWM method, respectively. The PS-DPWM generates $4f_{sw}$ equivalent switching frequency of output voltage. On the other hand, the PS-CDPWM generates only $f_{sw}$ equivalent switching frequency because one of two legs is always clamped. The harmonic characteristic is complementary opposite with the frequency of the output voltage. Therefore, the proposed method is suitable for a CHB multilevel inverter which consists of a large number of inverter cells.

To verify proposed modulation method, the simulation of power loss performs. In conventional PS-DPWM method,

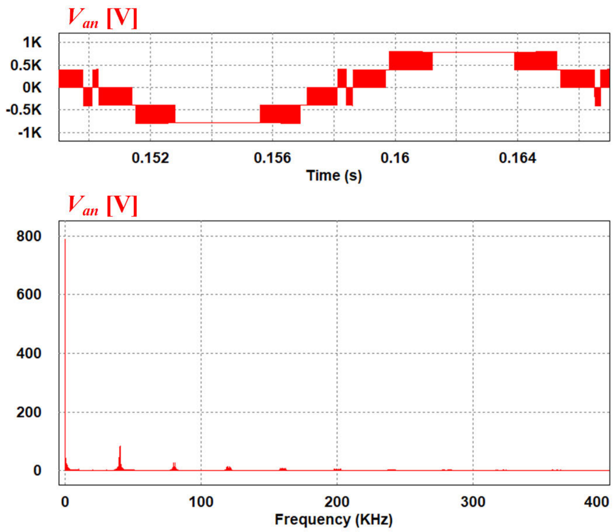



**FIGURE 13.** Frequency analysis results of output voltage in conventional PS-DPWM method when MI=1.0.

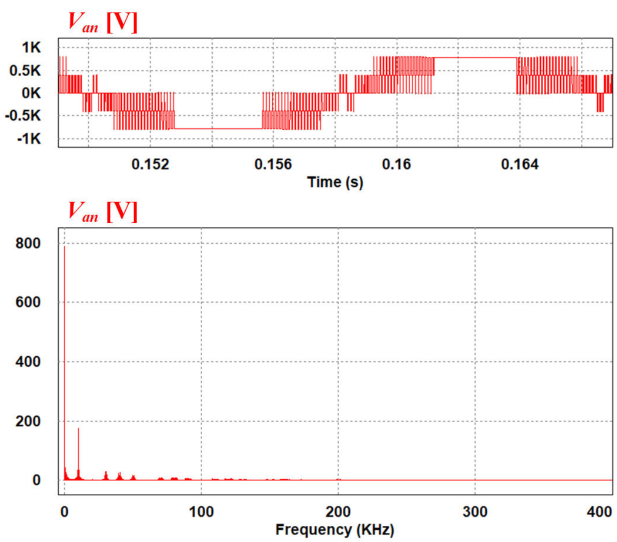



**FIGURE 14.** Frequency analysis results of output voltage in PS-CDPWM method when MI=1.0.

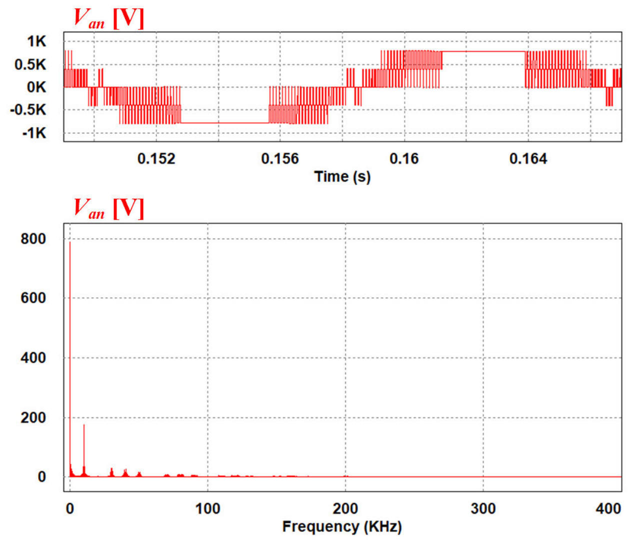



**FIGURE 15.** Frequency analysis results of output voltage in double rotation PS-CDPWM method when MI=1.0.

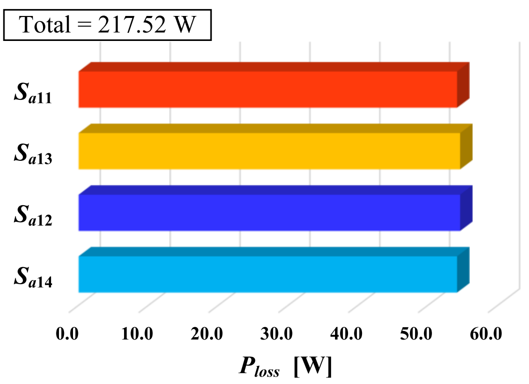



**FIGURE 16.** Switching loss simulation results of PS-DPWM method.

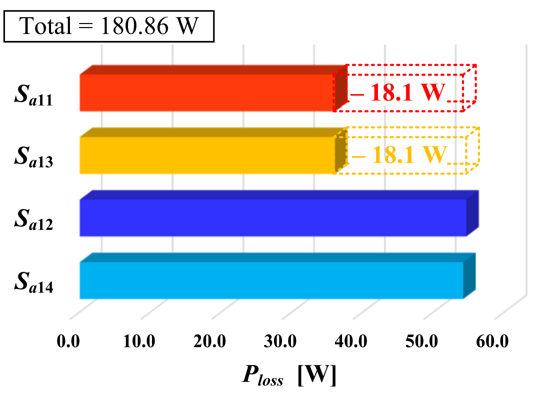
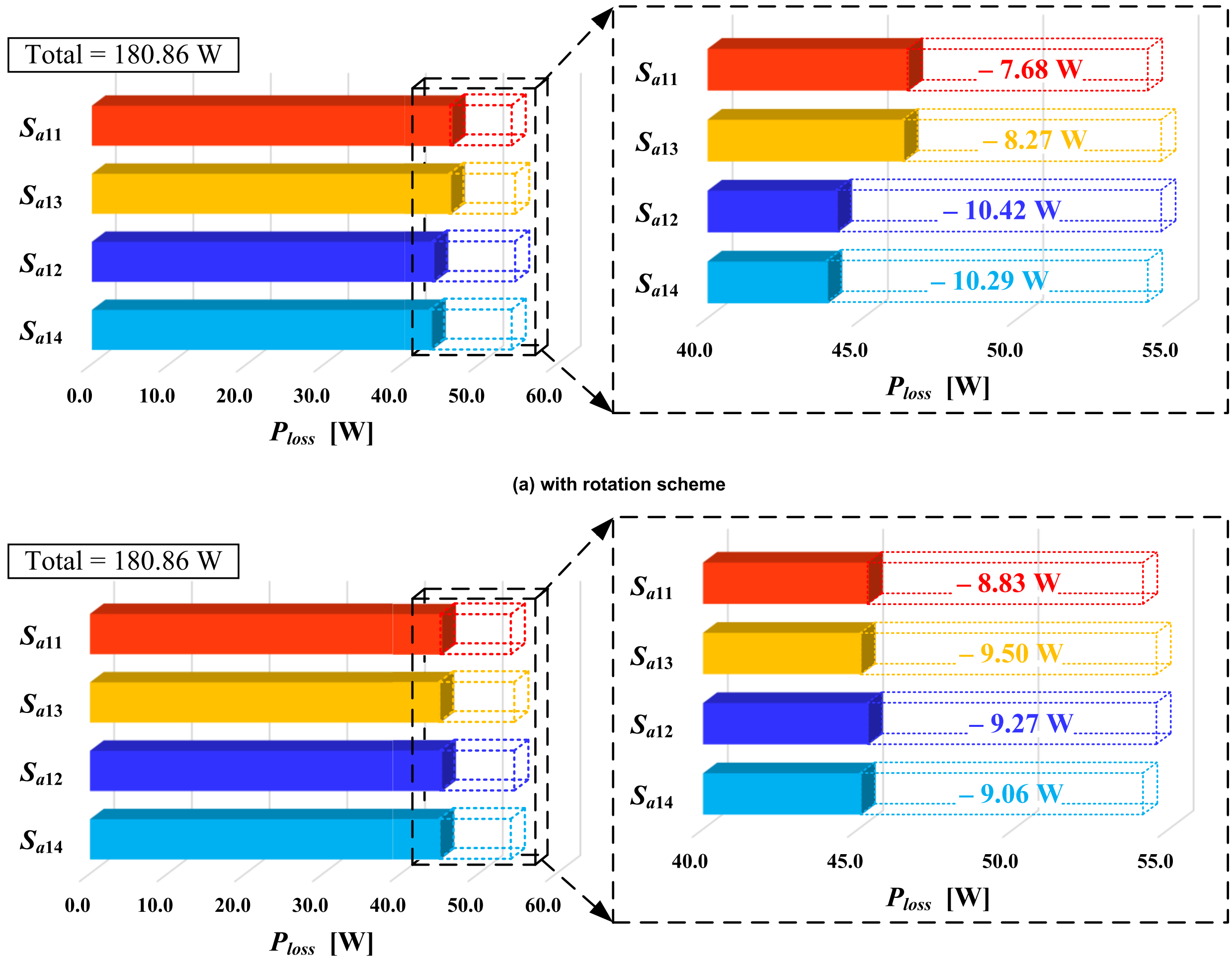



**FIGURE 17.** Switching loss simulation results of PS-CDPWM method.

the power loss each switch generates evenly as shown in Fig. 16. Fig. 17 is power loss simulation results that used PS-DPWM method and shows reduced switching loss compared with the conventional PS-DPWM method. However, the PS-CDPWM method generates unevenly power loss and decreases reliability of CHB multilevel inverter. If rotation period selected properly, the rotation scheme can solve uneven power loss problem each switch. Fig. 18(a) shows power loss each switch that adapted rotation PS-CDPWM method with 1/4 rotation period. As analyzed in section III-D, the 1/4 rotation period is unsuitable for solution about uneven power loss each switch. Therefore, the rotation scheme must be decided in consideration of power factor. As shown in Fig. 18(b), the double rotation PS-CDPWM method that applied rotation scheme considering for power factor distributes power loss evenly each switch. Therefore, the proposed method reduces power loss of switches effectively compared with conventional PS-DPWM method and the reliability of every switches are managed equally.




(a) with rotation scheme

(b) with double rotation scheme

**FIGURE 18.** Switching loss simulation results of rotation PS-CDPWM method depending on rotation scheme.

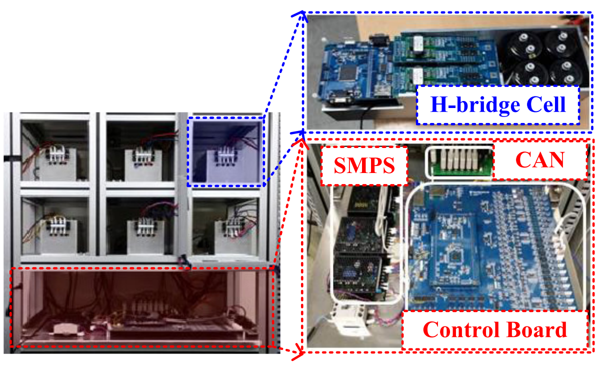



**FIGURE 19.** Hardware setup of the three-phase 5-level CHB Multilevel inverter.

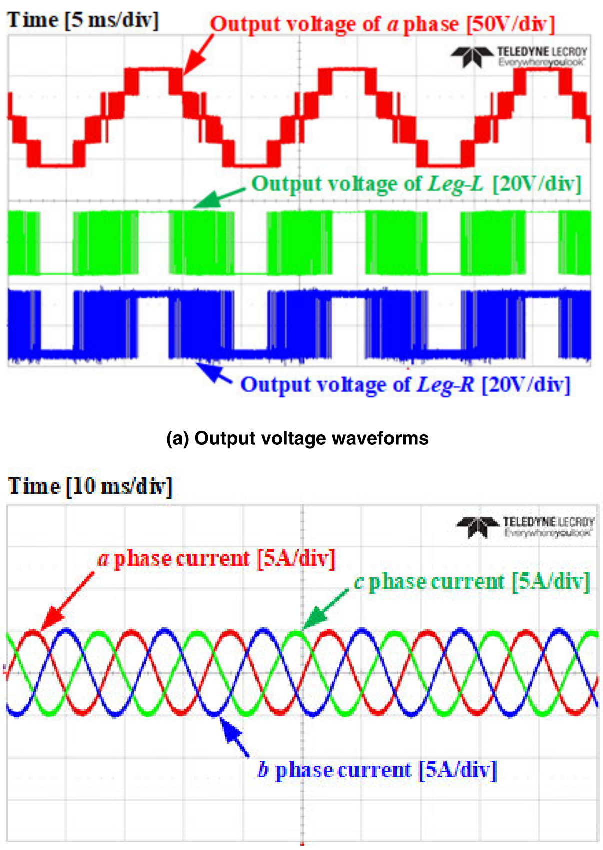
## V. EXPERIMENTAL RESULTS

The experiments are conducted to demonstrate the operation performance of the proposed modulation method by experimental set such as Fig. 19. The required DC source each H-bridge cell is 30V and it is small for the original purpose of CHB multilevel inverter. However, the voltage source level is enough to verify the switching operation results of the proposed modulation method. The others experimental parameters are listed in Table 2.

**TABLE 2.** Experimental parameters.

| PARAMETER | Values |
|---|---|
| DC voltage of each cell, $V_{dc}$ | 30 V |
| Total DC voltage per phase | 60 V |
| Switching frequency, $f_{sw}$ | 10 kHz |
| Fundamental frequency of output voltage | 60 Hz |
| Load resistance, $R$ / Filter inductance, $L$ | 10 Ω / 2 mH |

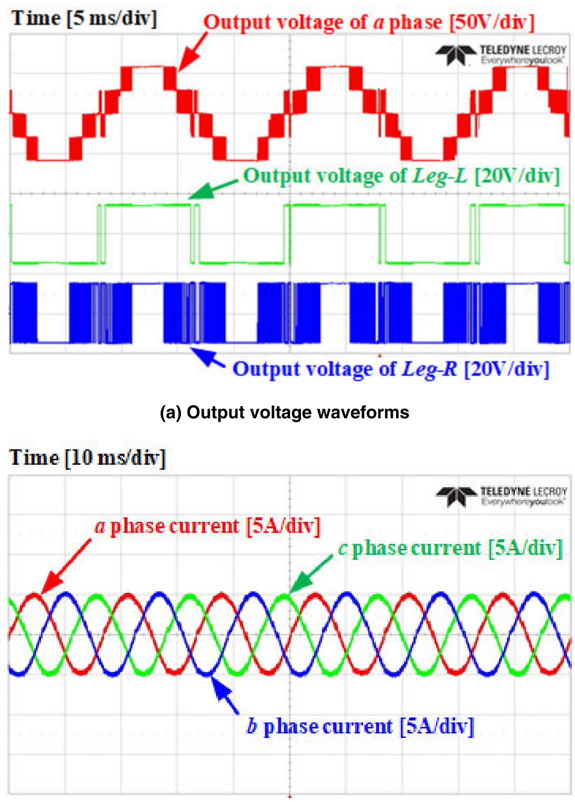
The experimental results of conventional PS-DPWM method is shown in Fig. 20, and each leg is not switched when discontinuous modulation period. As shown in Fig. 21, the *Leg-L* of H-bridge cell that applied PS-CDPWM method operates to fundamental frequency of output voltage and its power loss reduces. However, the reduced power




(a) Output voltage waveforms

(b) Output current waveforms

**FIGURE 20. Experimental results of the conventional PS-DPWM method.**




(a) Output voltage waveforms

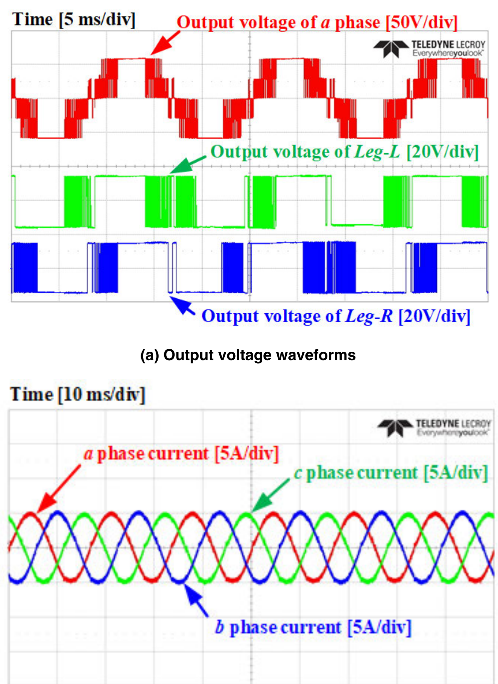
(b) Output current waveforms

**FIGURE 21. Experimental results of the PS-CDPWM method.**

loss is generated to only one leg each H-bridge cell. Fig. 22 shows experimental results waveforms of double rotation PS-CDPWM method, and it is solved unbalancing power loss by double rotation scheme. Additionally, the double rotation PS-CDPWM method maintain output performance compared to conventional PS-CDPWM method.

Because the power losses produce junction temperature of switches, the experiment of temperature measurement is conducted to verify the performance of proposed modulation method. To measure inside temperature of IGBT module, the hardware set of H-bridge cell is modified configuration as shown in Fig. 23(a). The parameters for experiments of temperature measurement are shown in Table 3, and the inside temperature of IGBT module (SK50GH12T4T, SEMIKRON) is measured by infrared camera (Ti-105, Fluke).

Fig. 23(b) shows internal configuration of IGBT module that consist of *Leg-L* and *Leg-R*. The *Leg-L* is expressed blue and it consist of $S_1$, $S_3$. Additionally, the *Leg-R* is expressed red and it consist of $S_2$, $S_4$. The inside temperature of IGBT module depending on modulation method are shown in Fig. 24. The conventional PS-DPWM method generates the most power losses, therefore it shows highest temperature as shown in Fig. 24(a). As shown in Fig. 24(b), the PS-CDPWM method reduces power losses of *Leg-L*

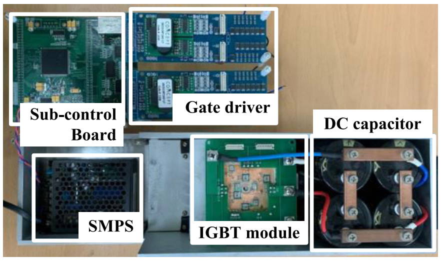



(a) Output voltage waveforms

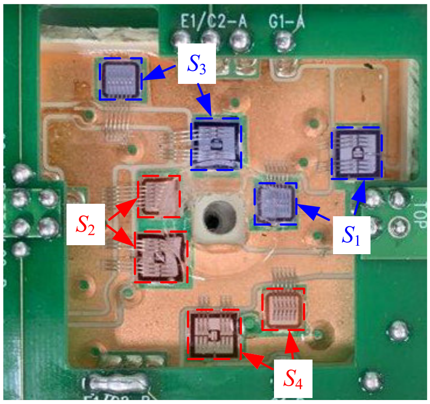
(b) Output current waveforms

**FIGURE 22. Experimental results of the double rotation PS-CDPWM method.**

and it decreases temperature of *Leg-L*. Fig. 24(c) is temperature of IGBT module with double rotation PS-CDPWM




(a) Overall configuration of H-bridge cell

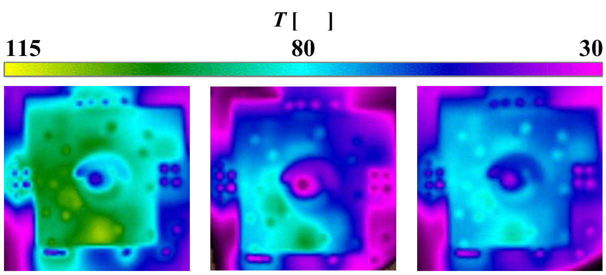



(b) Internal configuration of IGBT module (SK50GH12T4T)

**FIGURE 23.** **Modified configuration of H-bridge cell for experiment of temperature measurement.**

**TABLE 3.** **Experimental parameters of temperature measurement.**

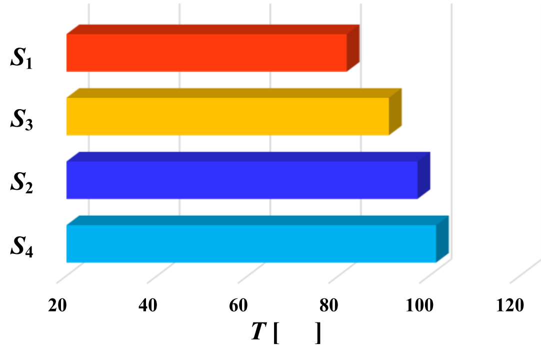
| PARAMETER | Values |
|---|---|
| Input power, $P_{in}$ | 1 kW |
| DC voltage of each cell, $V_{dc}$ | 200 V |
| Switching frequency, $f_{sw}$ | 10 kHz |
| Fundamental frequency of output voltage | 60 Hz |
| Load resistance, $R$ / Filter inductance, $L$ | 10 Ω / 2 mH |



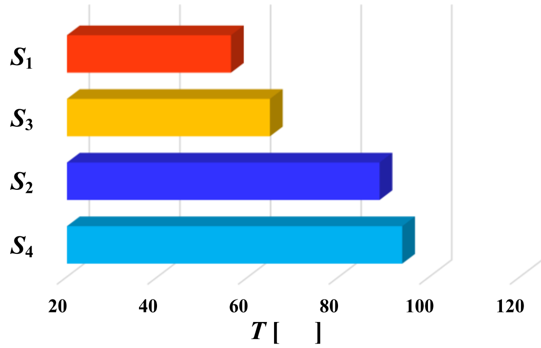

(a) (b) (C)

**FIGURE 24.** **Inside temperature of IGBT module (a) Conventional PS-DPWM method (b) PS-CDPWM method (c) Rotation PS-CDPWM method.**

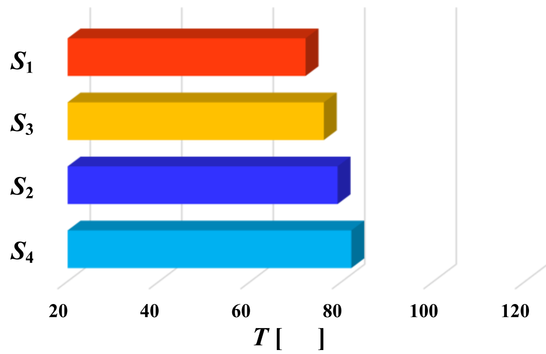
method that distributes power losses and temperature evenly. In the conventional PS-DPWM method and double rotation PS-CDPWM method, the cause of unbalancing temperature each leg is characteristic of hardware such as distance between components.




(a) Conventional PS-DPWM method




(b) PS-CDPWM method




(c) Double rotation PS-CDPWM method

**FIGURE 25.** **Comparison of inside temperature depending on modulation method.**

Fig. 25 shows comparison of inside temperature depending on modulation method as graph. The temperature of conventional PS-DPWM method shows the highest temperature and its average temperature is about 90°. The average temperature of PS-CDPWM method and double rotation PS-CPDWM method are about 75°, while the respective highest and lowest temperature are different. The failure mechanisms of switch are caused by thermal stress and thermal stress is produced by power losses. Therefore, the proposed modulation method extends effectively life time of switch and the reliability of CHB multilevel inverter increases.

## VI. CONCLUSION

This paper proposed an improved modulation method based on phase-shifted PWM scheme. Because switch is one of the most prone to failures components, the switch is important components to improve reliability and efficiency of CHB multilevel inverter. The life-time of switch is determined by thermal stress, therefore the proposed modulation method modified reference voltages each leg for reduction power loss that generates thermal stress. Furthermore, the switching loss distribution depending on the rotation period and power factor was discussed, and the rotation scheme to improve the reliability was proposed. The capability of proposed modulation method was verified by simulation results, and the performance of power loss reduction was verified experimentally in temperature measurement of IGBT module.

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