# Investigation of Switching Loss Reduction for the Matrix Converter Based on Virtual AC/DC/AC Conversion using Space Vector Modulation


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*Abstract*—**This paper proposes a space vector modulation based on the virtual AC/DC/AC conversion method for a matrix converter to reduce the switching loss. The switching loss of the matrix converter is not decided by only the number of switching times but also depending on the voltage and current in the selected switching devices based on the modulation. The proposed method can minimize the maximum instantaneous switching loss which is caused by the selection of switching state with the absolute maximum values in the input voltages and the output currents. This can be achieved by changing over the zero-vectors of virtual inverter in the proposed method. In this paper, the loss characteristics of the matrix converter using the proposed method are demonstrated experimentally. From the experimental result, it was confirmed that the proposed method can reduce the losses by 23.9 % in comparison with a conventional space vector modulation method.**



***Keywords-matrix converter; switching loss; virtual AC/DC/AC conversion; space vector modulation;***


## I. INTRODUCTION

Recently, the matrix converters which can convert an AC power supply voltage into an AC output voltage that delivers variable amplitude and frequency without the large energy storages, such as electrolytic capacitors, have been actively studied [1-11]. Matrix converters have advantages such as light-weight and long life-time due to no large passive components in the main circuit. In addition, matrix converters can achieve high efficiency because of less switching devices in the current path, in comparison with a Back-to-Back system, which consist of a PWM rectifier and a PWM inverter. Therefore, many control methods for matrix converters have been proposed and shown the following benefits, low switching loss, low input current harmonics, and low output voltage harmonics [6-11].

In order to reduce the harmonics components and switching loss, many PWM strategies of matrix converters have been studied [8-11]. Almost of the conventional method decrease the switching times of matrix converters, which aims at reducing the switching loss, similar to the other converter system.

However, the switching loss of the matrix converter is not determined by only the number of the switching times because the voltage and current of the switching devices are variable at any time. Moreover, the voltage and current of the devices are selected among the three-phase input voltage and output current. Thus, the instantaneous switching loss of a device occurs with nine combinations of the input voltages and the output currents. From these reasons, if the number of switching times is reduced, the total switching loss may not be decreased because large turn-on or turn-off loss occurs per switching. In other words, if the turn-on or turn-off loss per switching can be smaller, the total switching loss can be reduced in spite of the numbers of switching times.

This paper proposes a space vector modulation (SVM) control method to reduce the switching loss of matrix converters based on the virtual AC/DC/AC conversion method. The proposed method can minimize the maximum instantaneous switching loss which is generated at the device synthesizing the input voltage and the output current with the instantaneous absolute maximum value. The proposed method changes over the zero-vectors of the virtual inverter to avoid the switching of the device which connects between the input phase with the instantaneous absolute maximum voltage and the output phase with the instantaneous absolute maximum current. That is, the switching states synthesized by the proposed method do not have instantaneous maximum switching loss.

At first, this paper describes the SVM based on the virtual AC/DC/AC conversion. Second, the principle of the switching loss reduction by the proposed method is presented. Finally, the experiment using a 2-kW prototype is demonstrated to confirm the validity of the proposed method in term of loss characteristics. As these results, it is confirmed that the proposed SVM method can reduce the switching loss in the entire load power.

## II. VIRTUAL AC/DC/AC CONVERSION METHOD

Fig. 1 shows the circuit configuration of the matrix converter. Matrix converter consists of a LC filter and nine bidirectional switches. The virtual AC/DC/AC control method was proposed as a control technique for the matrix converter [4]. Then, the output phase voltages $^t[v_u\ v_v\ v_w]$ are shown as (1) using input phase voltage $^t[v_r\ v_s\ v_t]$.

$$\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} = \begin{bmatrix} d_{ru} & d_{su} & d_{tu} \\ d_{rv} & d_{sv} & d_{tv} \\ d_{rw} & d_{sw} & d_{tw} \end{bmatrix} \begin{bmatrix} v_r \\ v_s \\ v_t \end{bmatrix} \quad (1)$$

where $d_{nm}$ is duty ratio of the switch in the matrix converter ($n$: input phases, $m$: output phases) which is determined form 0 to 1.

Fig. 2 shows the virtual AC/DC/AC conversion system which is constructed by a rectifier and an inverter. The virtual AC/DC/AC control method considers the matrix converter as a virtual rectifier and a virtual inverter to obtain designated switching pulse commands. The rectifier is controlled as a current source type rectifier, and the inverter is controlled as a voltage source type inverter. The switching states in Fig. 1 can be expressed by the switching states in Fig. 2. Equation (2) expresses the formula for the duty composition in a matrix converter.

$$\begin{bmatrix} d_{ru} & d_{su} & d_{tu} \\ d_{rv} & d_{sv} & d_{tv} \\ d_{rw} & d_{sw} & d_{tw} \end{bmatrix} = \begin{bmatrix} d_{up} & d_{un} \\ d_{vp} & d_{vn} \\ d_{wp} & d_{wn} \end{bmatrix} \begin{bmatrix} d_{rp} & d_{sp} & d_{tp} \\ d_{rn} & d_{sn} & d_{tn} \end{bmatrix} \quad (2)$$

where, $d_{ij}$ is duty of the switch in the virtual AC/DC/AC converter ($i$: $r, s, t, u, v, w$, $j$: $p, n$).

According to (2), the duty commands of the virtual rectifier and the virtual inverter are multiplied by each upper arm (p side) and lower arm (n side), respectively. Then, the duty commands of the matrix converter are obtained from the multiplied duty commands.

### *A. Determination of the virtual rectifier vector*

Fig. 3 shows the space vector diagram of the virtual rectifier. $I_1 \sim I_6$ are the input phase current vectors. Index of the input current vectors represents the switching states of the virtual rectifier switches. For example, (RT) indicates that $S_{rp}$ and $S_{tn}$ are in ON state and other switches are in OFF state in Fig. 2.

It is assumed that the command vector of the virtual rectifier is in sector 1 in Fig. 3. Then, α-axis and β-axis components of the input current command vector $\boldsymbol{I_{in}}^*$ are expressed by α-axis and β-axis components of the input phase current vectors $\boldsymbol{I_1}$ and $\boldsymbol{I_2}$, and its duties are obtained by (3).

$$\begin{bmatrix} I_{in\alpha}^* \\ I_{in\beta}^* \\ 1 \end{bmatrix} = \begin{bmatrix} I_{1\alpha} & I_{2\alpha} & 0 \\ I_{1\beta} & I_{2\beta} & 0 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} d_{in1} \\ d_{in2} \\ d_{in0} \end{bmatrix} \quad (3)$$

where, $d_{ink}$ is duty ratio of the input phase current vector in the selected sector ($k$: 0 ~ 6).

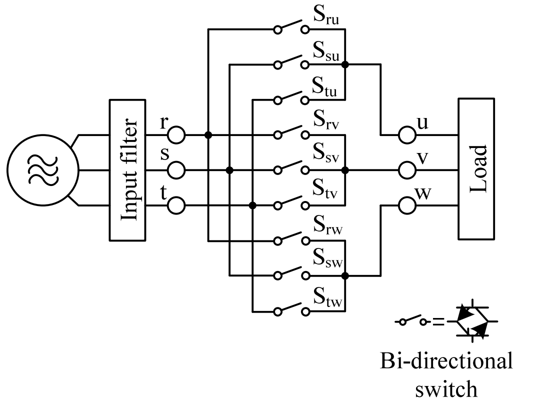



Figure 1. Circuit configuration of the matrix converter.

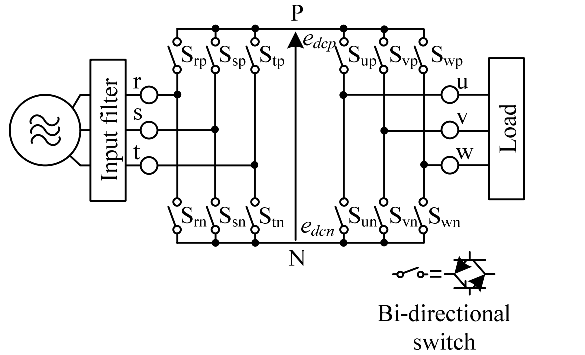



Figure 2. Virtual AC/DC/AC converter which generates same input and output waveforms with the matrix converter in Figure 1.

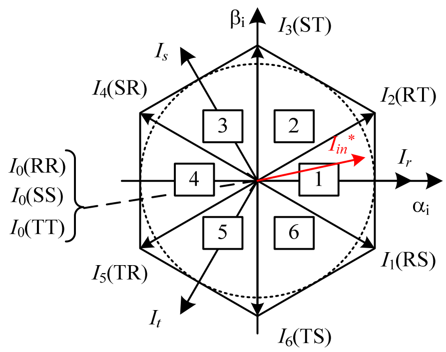



Figure 3. Space vector diagram of the virtual rectifier.

### *B. Determination of the virtual inverter vector*

Fig. 4 shows the space vector diagram of the virtual inverter. $V_1 \sim V_6$ are the output phase voltage vectors. Index of the output voltage vectors are the switching states for the virtual inverter switches. For example, (110) indicates that $S_{up}$, $S_{vp}$ and $S_{wn}$ are in ON state and other switches are in OFF state in Fig. 2.

It is assumed that the command vector of the virtual inverter is in sector 1 of Fig. 4. Then, α-axis and β-axis components of the output voltage command vector $\boldsymbol{V_{out}}^*$ are expressed by α-axis and β-axis components of the output phase voltage vectors $\boldsymbol{V_1}$ and $\boldsymbol{V_2}$, and its duties are obtained by (4).

$$\begin{bmatrix} V_{out\alpha}^{\ *} \\ V_{out\beta}^{\ *} \\ 1 \end{bmatrix} = \begin{bmatrix} V_{1\alpha} & V_{2\alpha} & 0 \\ V_{1\beta} & V_{2\beta} & 0 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} d_{out1} \\ d_{out2} \\ d_{out0} \end{bmatrix} \tag{4}$$

where, $d_{outl}$ is duty ratio of the output phase voltage vector in the selected sector ($l$: 0 ~ 6).

### *C. Composition of the switching states*

The switching state of the matrix converter based on the virtual AC/DC/AC conversion method depends on the switching states of the virtual rectifier and inverter. Therefore, if the virtual inverter outputs zero-vector which means that the output voltage is zero, the matrix converter can outputs three zero-vectors due to the switching states of the virtual rectifier.

Table I shows the switching states of the matrix converter focused on the zero-vector of the virtual inverter. Then, for example, (RRR) of the matrix converter vector indicates that all output phases connect to input R-phase. The inverter has two zero-vectors which are expressed by (000) and (111). As shown in Table I, the matrix converter outputs one of three zero-vectors when the inverter outputs zero-vector. Therefore, the matrix converter based on the virtual conversion method has redundancy to the zero-vectors. Any zero-vectors in the virtual inverter can be selected because the zero-vectors does not affect the input and output waveforms.

As shown Table II, when switching state changes from (TRT) to (TTT), v-phase is connected from R-phase to T-phase only. On the other hands, when switching state changes from (TRT) to (RRR), u-phase and w-phase are in switching. Therefore, switching states are difference due to selected inverter zero-vector. In addition, it is confirmed that the instantaneous switching loss depends on not only the switching times but also the relationship between the input and output phases due to the selected redundant zero-vector of the virtual inverter [11].

## III. REDUCTION FOR SWITCHING LOSS BY ZERO-VECTORS

It is assumed that the command vector of the virtual rectifier is in sector 1 in Fig. 3 and the command vector of the virtual inverter is in sector 1 in Fig. 4. Then, the command vector of the virtual rectifier is synthesized by the input phase current vectors, (RS), (RT) and (RR). Then, it is confirmed that $S_{rp}$ in the virtual rectifier is in on-state during sector 1. In other words, the maximum phase in the input voltages is r-phase during sector 1 in order to get the largest voltage at the virtual DC-link part in Fig. 2. Thus, the maximum input voltage phase is distinguished from other two input phases by on-state switch during its sector.

Fig. 5 shows the decision method of the absolute maximum voltage phase using the middle phase pole in the virtual inverter. This is a method to distinguish the output phase with the absolute maximum current value without sensors. Note that this method can be used when the output power factor is almost unity only. The output phase with the

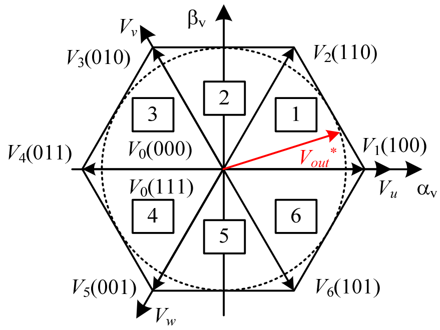



Figure 4. Space vector diagram of the virtual inverter.

TABLE I. SWITCHING STATES OF THE MATRIX CONVERTER FOCUSED ON THE ZERO-VECTORS OF THE VIRTUAL INVERTER.

| Rectifier vector | Inverter vector | Matrix converter vector |
|---|---|---|
| RS | 000 | SSS |
| | 111 | RRR |
| RT | 000 | TTT |
| | 111 | RRR |

TABLE II. THE DIFFERENCE OF SWITCHING PHASE DUE TO THE REDUNDANCY OF ZERO-VECTOR

| Before | After |
|---|---|
| TRT | TTT |
| TRT | RRR |

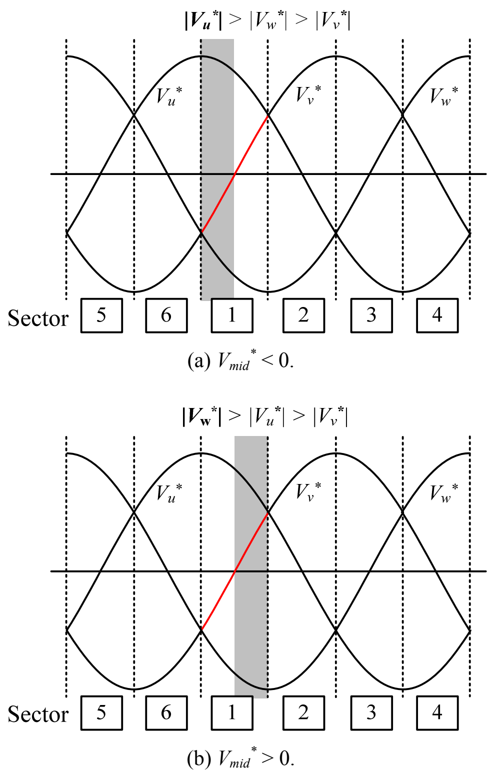



Figure 5. Decision method of the absolute maximum voltage phase using middle phase using the middle phase pole in the virtual inverter.

absolute maximum phase voltage command changes according to pole of the middle phase voltage command ($V_{mid}^*$) in Fig. 5. At sector 1 in Fig. 5, when the pole of the middle phase voltage command is negative, it can be confirmed that the maximum voltage command phase is u-phase. On the other hand, when the pole of the middle phase voltage command is positive, the maximum voltage command phase is w-phase. When the output power factor is almost unity, the output current phase corresponds to the output voltage command. Hence, the maximum output current phase is distinguished from other two output phases by the method in Fig. 5.

Table III shows the composition of the switching states for the matrix converter in sector 1 of the space vector diagram of the virtual rectifier and in sector 1 of the space vector diagram of the virtual inverter. As mentioned above, in these sectors, the input phase with the instantaneous absolute maximum voltage is r-phase and the output phase with the instantaneous absolute maximum current is u-phase during $V_{mid}^* < 0$ or w-phase during $V_{mid}^* > 0$. According to Table 3, in region of $V_{mid}^* < 0$, u-phase is connected to r-phase in on-state at any time when the zero-vector of the virtual inverter is (111). Therefore, the maximum instantaneous switching loss is not generated because $S_{ru}$ in Fig. 1 is not in switching operation. If the zero-vector (000) is selected in this region, $S_{ru}$ is in switching operation and the maximum instantaneous switching loss occurs. On the other hand, in region of $V_{mid}^* > 0$, w-phase is connected to r-phase with the least switching times when the zero-vector of the virtual inverter is (000). Thus, the maximum instantaneous switching loss is minimized because $S_{rw}$ in Fig. 1 is in switching operation with the least switching times. If the zero-vector (111) is selected in this region, the switching times of $S_{rw}$ will increase and the maximum instantaneous switching loss is generated more.

Fig. 6 shows flowchart for the proposed method to generate the duties for matrix converter. Input command vector $\boldsymbol{I_{in}}^*$ is obtained by transforming input 3-phase current commands $i_r^*$, $i_s^*$, $i_t^*$ to αβ-frame. Next, the input sector is checked by the input current command vector. Then, the virtual rectifier duties can be calculated by (3) and distributed to the switches composing the input phase current vector in the selected sector. The virtual inverter duties are also calculated by (4) using the output 3-phase voltage commands. Each vector duty is transformed to the duties of the inverter switches by (5) and (6).

$$\begin{bmatrix} d_{up} \\ d_{vp} \\ d_{wp} \end{bmatrix} = \begin{bmatrix} s_{up1} & s_{up2} & s_{up0} \\ s_{vp1} & s_{vp2} & s_{vp0} \\ s_{wp1} & s_{wp2} & s_{wp0} \end{bmatrix} \begin{bmatrix} d_{out1} \\ d_{out2} \\ d_{out0} \end{bmatrix} \tag{5}$$

$$\begin{cases} d_{un} = 1 - d_{up} \\ d_{vn} = 1 - d_{vp} \\ d_{wn} = 1 - d_{wp} \end{cases} \tag{6}$$

TABLE III. COMPOSITION OF THE SWITCHING STATES FOR MATRIX CONVERTER IN SECTOR 1 OF THE SPACE VECTOR DIAGRAM OF THE VIRTUAL RECTIFIER AND IN SECTOR 1 OF THE SPACE VECTOR DIAGRAM OF THE VIRTUAL INVERTER.

| | Virtual rectifier | Virtual inverter | Matrix converter |
|---|---|---|---|
| $V_{mid}^*$<0 | RS | 110 | RRS |
| | | 100 | RSS |
| | | 111 | RRR |
| | RT | 110 | RRT |
| | | 100 | RTT |
| | | 111 | RRR |
| | RR | 110 | RRR |
| | | 100 | RRR |
| | | 111 | RRR |
| $V_{mid}^*$>0 | RS | 110 | RRS |
| | | 100 | RSS |
| | | 000 | SSS |
| | RT | 110 | RRT |
| | | 100 | RTT |
| | | 000 | TTT |
| | RR | 110 | RRR |
| | | 100 | RRR |
| | | 000 | RRR |

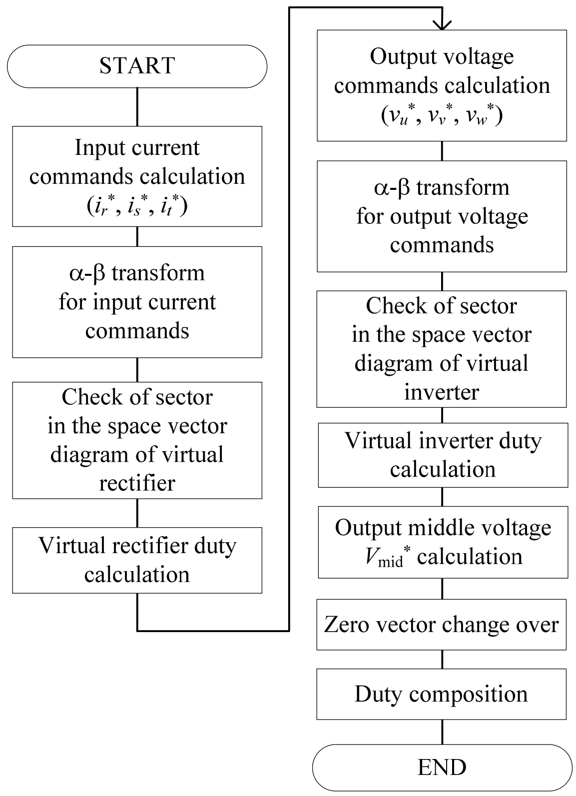



Figure 6. Flowchart to generating duty for matrix converter.

TABLE IV. EXPERIMENTAL PARAMETERS.

| | |
|---|---|
| Input voltage (line-to-line) | 200V |
| Input frequency | 50Hz |
| Output frequency | 45Hz |
| Modulation index of MC | 0.9 |
| Load | R-L (1600W) |
| Carrier frequency | 10kHz |
| LC filter $f_c$ | 980Hz |

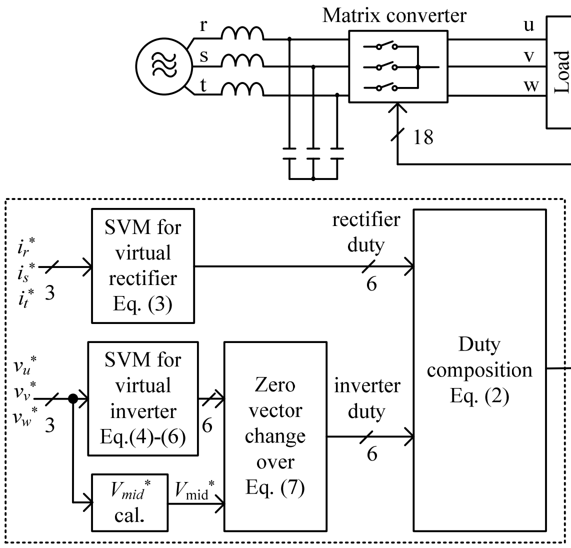
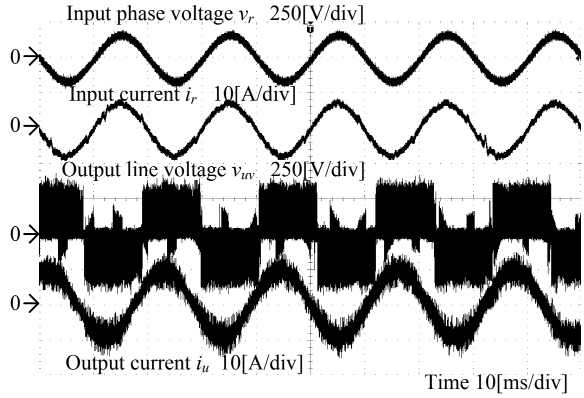
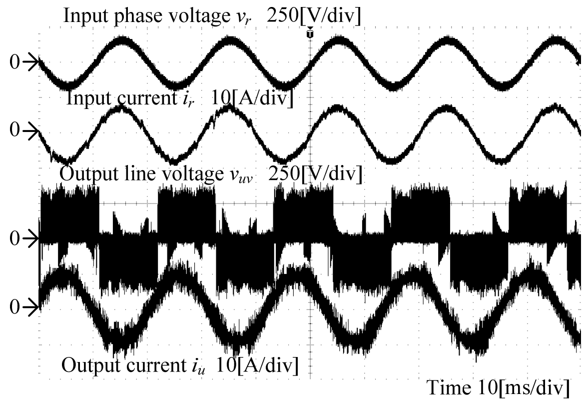



Figure 7. Control block diagram of the proposed SVM method. The block of " zero-vector change over" is added to the control block diagram of the conventional SVM method




(a) The convertional SVM method.




(b) The proposed SVM method.

Figure 8. Input and output waveforms in steady state. The proposed SVM method can achieve the equal or higher performance in comparison with the conventional SVM method.

where, $s_{xyz}$ is switching function. Then, $s_{xyz}$ = 1 corresponds to on-state and $s_{xyz}$ = 0 corresponds to off-state ($x$: $u$, $v$, $w$, $y$: $p$, $n$, $z$: 0~6).

At the block of "zero-vector change over" in the flowchart, the inverter zero-vector is changed by pole of the middle output voltage, as shown (7).

$$\begin{cases} s_{up0} = 1, \quad s_{vp0} = 1, \quad s_{wp0} = 1 \ (v_{mid} < 0) \\ s_{up0} = 0, \quad s_{vp0} = 0, \quad s_{wp0} = 0 \ (v_{mid} > 0) \end{cases} \tag{7}$$

## IV. EXPERIMENTAL RESULTS

Table IV shows the experimental parameters. In addition, a conventional SVM that does not change over the virtual inverter zero-vectors was experimented, too.

Fig. 7 shows the control block diagram of the proposed SVM method. The proposed method adds the "Zero-vector change over" block to the conventional control block diagram.

Fig. 8 (a) and (b) shows the experimental waveforms of the conventional SVM and proposed SVM respectively.. The input current and output current is controlled as sinusoidal waveforms and unity input power factor is obtained in both control methods. The total harmonic distortion (THD) in the input current and output current are 4.8% and 2.1 % in Fig. 8 (a). On the other hand, the THD in the input current and output current are 4.4 % and 1.4% in Fig. 8 (b). Thus, the proposed SVM method can achieve the equal or higher performance in comparison with the conventional SVM method.

Fig. 9 shows a loss analysis between the proposed and conventional SVM methods. In Fig. 9, the proposed method can reduce loss over the entire load power region, and the loss by approximately 23.9% can be reduced in comparison with that of the conventional SVM method at 1.6-kW load. Then, the efficiency of the proposed SVM method is 94.1 %. Hence, the proposed SVM can reduce the switching loss of matrix converter because the zero-vectors of the virtual inverter are changed.

Fig. 10 shows the switching states between the conventional and proposed SVM methods when the input sector is 1 and the output sector is 1. The proposed SVM method does not select the zero-vector (TTT) which is selected by conventional SVM method. This is the evidence that the proposed SVM method changes two zero-vectors and uses only one zero-vector of the virtual inverter to avoid the switching state to generate the instantaneous maximum switching loss. In addition, the proposed SVM method reduces switching times by two times because the selected zero-vector can be combined at once. In the conventional SVM method, the zero-vectors at the carrier peak and at the carrier bottom are different and are distributed equally, respectively. However, the proposed SVM method uses the only vector. Thus, the proposed SVM method can distribute the zero-vector at the carrier bottom and reduce the switching time. Therefore, the proposed SVM method could reduce a loss as compared with conventional SVM method.

## V. CONCLUSION

This paper proposes a space vector modulation (SVM) control method in order to reduce the switching loss of a matrix converter based on the virtual AC/DC/AC conversion. The proposed method focuses on the instantaneous maximum switching loss which is generated at the device synthesizing the input voltage and the output current with the instantaneous absolute maximum value. In other word, the proposed method can reduce the switching loss by the reduction of the switching states which generate instantaneous maximum switching loss, not the reduction of the switching times. The reduction of the instantaneous maximum switching loss is realized by changing the zero-vector of the virtual inverter. From the experimental results, it is confirmed that the proposed method can control matrix converter with input and output sinusoidal waveforms. In addition, the proposed method can reduce loss over the entire load power region, and the loss by approximately 23.9% can be reduced in comparison with that of the conventional SVM method at 1.6-kW load. Finally, from the transition of switching states in 1 carrier period, it is confirmed that the proposed SVM method does not select the zero-vector which generates the instantaneous maximum switching loss. Therefore, the proposed SVM method is useful to reduce the switching loss of matrix converters.

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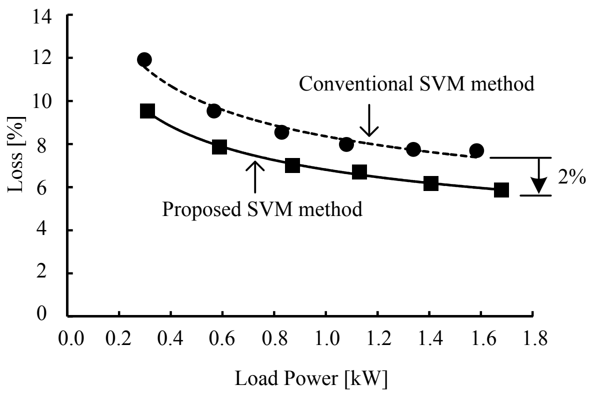


Figure 9. Loss characteristics of the proposed and conventional PWM methods. The proposed method can reduce loss over the entire load power region, and the loss by approximately 23.9% can be reduced in comparison with that of the conventional SVM method at 1.6-kW load.

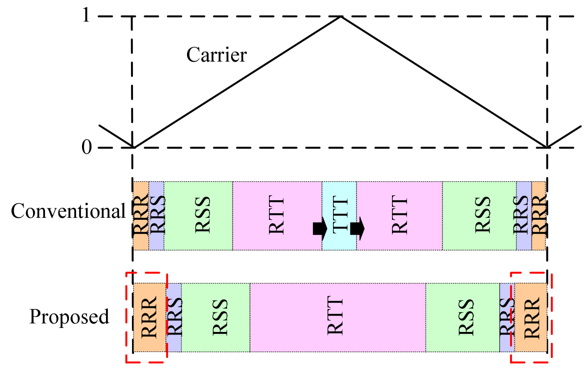


Figure 10. Switching states in 1 carrier period. The conventional SVM method selects two zero-vectors, RRR and TTT. However the proposed SVM method does not select the zero-vector TTT which generates the instantaneous maximum switching loss.

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