Halt Sequence for Matrix Converter to Suppress Increase of Snubber Capacitor Voltage during Motor Regeneration

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Abstract— **This paper proposes a halt sequence for a matrix converter to overcome the overvoltage and overcurrent problems in the case of grid faults in regeneration. The proposed halt sequence short-circuits PMSM to avoid the regenerating current which flows into the snubber capacitor. The proposed method consists of two sequences; Sequence I controls the q-axis current to reach zero and PMSM becomes in the flux-weakening region. Then, Sequence II short-circuits PMSM to avert the regenerating current flowing into the snubber capacitor. In Sequence II, the current direction of the bi-directional switches is restricted by gate signal in order to achieve to cut the current off automatically at the zero-crossing point of the motor current. The experimental results demonstrate that the rise of the snubber capacitor voltage is less than 16% of the rated snubber voltage.**

Keywords— Permanent Magnet Synchronous Motor; Matrix converter; Halt sequence; Dynamic braking circuit;

I. Introduction

Recently, power converters in regenerative adjustable-speed drive system such as a crane, an elevator and a flywheel energy storage system are required from the view point of the improvement of long life time and the reduction of the volume [1-6]. A matrix converter, which is one of the AC/AC direct converters, is expected to achieve smaller volume, higher efficiency and longer lifetime than a back-to-back (BTB) system which consists of a three-phase PWM rectifier and a three-phase PWM inverter [7-9]. Therefore, the matrix converter is used for above regeneration systems. When a film capacitor or a ceramic capacitor with a small capacitance is used as a snubber capacitor in the snubber circuit, the reduction of the volume and the extension of lifetime are achieved. However, the snubber capacitor voltage increases rapidly in case that all bi-directional switches in the matrix converter are turned off simultaneously when the grid faults halt the matrix converter which has the snubber capacitor with small capacitance while in the regeneration. Then, when the snubber capacitor voltage exceeds the rated voltage, the switching devices are broken. Therefore, it is necessary to suppress the rise of the snubber voltage when grid faults happen.

As one of the conventional solutions to suppress the increase of the snubber voltage, a dynamic brake circuit is connected in parallel with the snubber capacitor [9]. When the snubber voltage is over the threshold voltage, the resistance in the brake chopper circuit consumes the regeneration energy. Nevertheless, the dynamic brake circuit requires a large-capacity resistance and a switching device. Furthermore, it is undesirable that the cost and volume of the dynamic brake circuit in the regenerative adjustable-speed system.

The authors have proposed a halt sequence that short-circuits the terminal of PMSM according to the motor current when the grid is cutoff during the regeneration [10]. This method avoids the overvoltage of the DC-link capacitor, and also prevents the overcurrent problem in the BTB system. However, when each switching device is turned off around zero-crossing point of corresponding motor current during the short-circuit of PMSM of this technique, the snubber voltage is increased by the surge current because it is difficult to detect correctly the zero-crossing point of motor current. Therefore, this technique directly cannot be applied to the matrix converter without modifications.

This paper proposes a halt sequence for the matrix converter. The proposed halt sequence consists of two sequences; Sequence I controls the q-axis current to reach zero without a current regulator and achieves the flux-weakening operation to reduce the output terminal voltage whereas the hysteresis control in Sequence I maintains the filter capacitor voltage within a certain range. After Sequence I, Sequence II short-circuits PMSM to prevent its current flowing into the snubber circuit and turns each bi-directional switch off each time when the current reaches zero. This paper is organized as follows; first, the principle of the proposed halt sequence method is introduced. Next, the fundamental operation is confirmed in the simulation. Finally, the effectiveness of suppressing the increase of the snubber capacitor voltage in the proposed halt sequence is evaluated in experiments.

II. Principle of Halt Sequence for Matrix Converter

A. Overvoltage problem

Fig. 1 shows the system configuration of the motor drive system using the matrix converter in order to control a

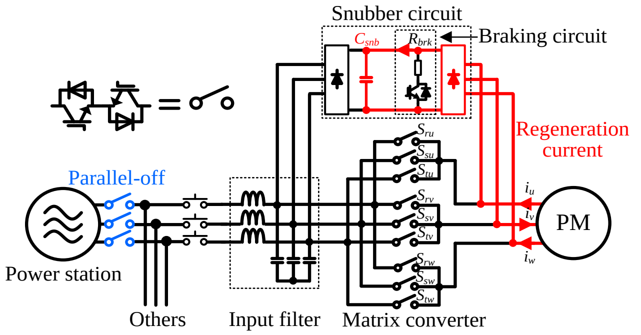


Fig. 1. Configuration of the matrix converter for a motor drive system. The snubber circuit includes a braking circuit which consists of a switching device and a large-capacity resistance.

Permanent Magnet Synchronous Machine (PMSM). In general, the matrix converter includes the snubber circuit to absorb a surge current and a surge voltage. When the surge current flows or the surge voltage occurs, the snubber capacitor C_{snb} in snubber circuit absorbs the surge current and the surge voltage. In addition, a magnetic contactor is placed between the grid side and the matrix converter for the protection. The dynamic brake circuit is connected in parallel with the snubber capacitor to suppress the rise of the snubber capacitor voltage which happens eventually due to the absorption of the surge voltage and the surge current. However, when the grid faults halt the matrix converter with the snubber capacitor during motor regeneration suddenly, it is difficult to suppress the rise of the snubber capacitor voltage by only using the discharge resistance because a large regeneration current flows to the snubber circuit. Therefore, in order to suppress the rise of the snubber capacitor voltage during above accident, a braking circuit is added to the snubber circuit. However, it is preferable that the cost and volume is increased due to the dynamic brake circuit.

B. Proposed halt sequence

The regeneration power P from PMSM depends on the rotating speed and the braking torque of PMSM.

$$P = \omega T \tag{1}$$

where ω is the rotational speed and T is the torque of the PMSM. In addition, the output torque of the PMSM is given by (2).

$$T = P_n i_q \left\{ \sqrt{3}\Psi_e + \left(L_d - L_q\right) i_d \right\} \tag{2}$$

where Ψ_e is the linkage magnetic flux of armature by permanent magnet, L_d is the d-axis inductance, L_q is the q-axis inductance, P_n is the number of the pairs of poles, and i_d and i_q are the d- and q-axis current. From (2), it is understood that the negative torque causes the rise of the snubber capacitor voltage if the q-axis current flows into negative direction. Thus, the q-axis current should reach zero in the halt sequence as fast as possible in order to preclude the overvoltage at the snubber capacitor voltage.

Fig. 2 shows the operation flow chart of the proposed halt sequence. Sequence I controls the q-axis current to reach zero and achieves the flux-weakening operation to reduce the output terminal voltage without using a current regulator whereas the hysteresis control, which selects the switching patterns to charge and discharge the filter capacitor, maintains its voltage within a certain range. After the q-axis current becomes zero,

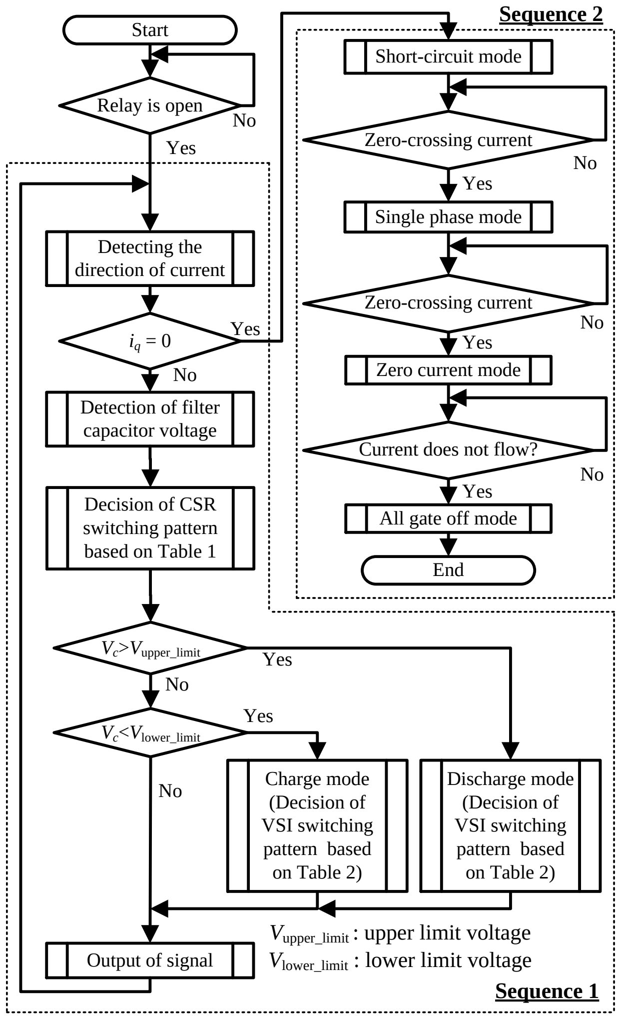


Fig 2. Flow chart of the proposed halt sequence for the matrix converter.

Sequence II is implemented in order to conduct the short-circuit mode until the motor current is interrupted by Sequence II. It has been observed that Sequence II alone can achieve to prevent the snubber capacitor from the rapid voltage rise, because the regeneration current is circulating in the matrix converter. However, the short-circuit current will increase by the high electromotive force of PMSM drastically in high speed region. In the worst case, the irreversible demagnetization of the PMSM happens because of the large short-circuit current. In addition, it is necessary to implement with higher current rating switching devices in the matrix converter. Therefore, Sequence I is introduced before Sequence II in order to preclude the large short-circuit current with the reducing the output terminal voltage. Sequence I suppresses the maximum current to below three times of the rating current of PMSM, and then generally the irreversible demagnetization in PMSM does not occur.

Fig. 3 shows an example of Sequence I. The magnetic contactor is off because of the grid faults before Sequence I starts. Therefore, the filter capacitor voltage is maintained by only the charge and discharge current which flows from PMSM. Besides, this proposed halt sequence selects the switching pattern based on the virtual AC/DC/AC conversion.

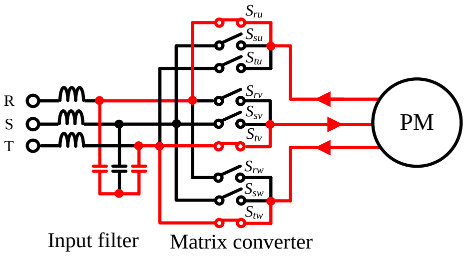


Fig. 3. Example of Sequence I.

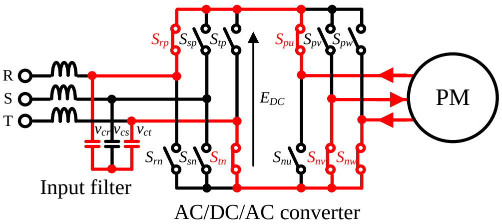


Fig. 4 Virtual AC/DC/AC converter which generates same input and output waveform with the matrix converter in Fig. 3

Fig. 4 shows the virtual AC/DC/AC conversion system which is constructed by a current source rectifier (CSR) and a voltage source inverter (VSI). The virtual AC/DC/AC control method separates the input current control strategy and the output voltage control strategy because the matrix converter is considered as a virtual CSR and a virtual VSI to obtain designated switching pulse commands [8]. The switching states in Fig. 3 can be expressed by that in Fig. 4. Equation (3) expresses the formula for the switching states in the matrix converter.

$$\begin{bmatrix} S_{ru} & S_{su} & S_{tu} \\ S_{rv} & S_{sv} & S_{tv} \\ S_{rw} & S_{sw} & S_{tw} \end{bmatrix} = \begin{bmatrix} S_{up} & S_{un} \\ S_{vp} & S_{vn} \\ S_{wp} & S_{wn} \end{bmatrix} \begin{bmatrix} S_{rp} & S_{sp} & S_{tp} \\ S_{rn} & S_{sn} & S_{tn} \end{bmatrix} \qquad (3)$$

where, S_{ij} is the switching function of the switch S_{ij} in the virtual AC/DC/AC converter.

Fig. 5 shows the relationship between the filter capacitor voltage and the state number. Table 1 shows the switching table of the virtual CSR. The bi-directional switch, which is connected to the medium phase voltage, is off in Sequence I. In other words, the matrix converter acts as two-level inverter which has a DC-link voltage equaling to the difference between the maximum phase voltage and the minimum phase voltage.

Fig. 6 shows the output voltage vector of the charging mode and the discharging mode toward the motor current vector in Sequence I. The instantaneous power p_{out} does not occur when the output voltage vector crosses the motor current vector at the right angles as shown in Fig. 6. Nevertheless, the instantaneous power p_{out} cannot always become zero because the matrix converter which acts as the two-level inverter has only six active voltage vectors. The six active voltage vectors of the matrix converter separates the charging voltage vector and discharging voltage vector. Therefore, Sequence I selects the switching pattern to charge and discharge the filter capacitor to keep its voltage according the current direction while the instantaneous power p_{out} is adjusted to reach zero. Finally, the q-axis current turns zero and PMSM is in the flux-weakening region because the the energy stored in the q-axis inductance is stored to the d-axis inductance by the charging and discharging vectors in the matrix converter.

Table 2 shows the switching table of the virtual voltage source inverter. The discharging mode selects the voltage command vector which is delayed by a 30 to 90 degrees toward the motor current vector. Similarly, the charge mode selects the output voltage vector which is delayed by a 90 to 150 degrees toward the motor current vector. The output voltage vector which is applied to PMSM is delayed a 60 to 120 degree toward the motor current vector by alternating the charging mode with

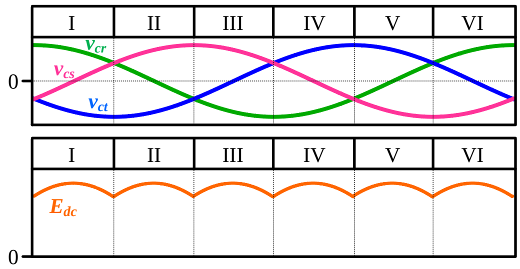


Fig. 5. Input voltage, virtual DC-link voltage and state number.

Table 1. Switching pattern of the current source rectifier at Sequence I.

	Max/Mid/Min			State of switch of rectifier					
	v_r	v_s	v_t	S_{rp}	S_{sp}	S_{tp}	S_{rn}	S_{sn}	S_{tn}
I	MAX	MID	MIN	ON	OFF	OFF	OFF	OFF	ON
II	MID	MAX	MIN	OFF	ON	OFF	OFF	OFF	ON
III	MIN	MAX	MID	OFF	ON	OFF	ON	OFF	OFF
IV	MIN	MID	MAX	OFF	OFF	ON	ON	OFF	OFF
V	MID	MIN	MAX	OFF	OFF	ON	OFF	ON	OFF
VI	MAX	MIN	MID	ON	OFF	OFF	OFF	ON	OFF

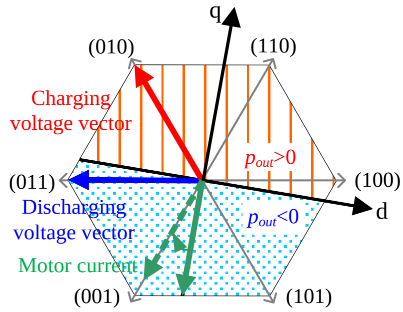
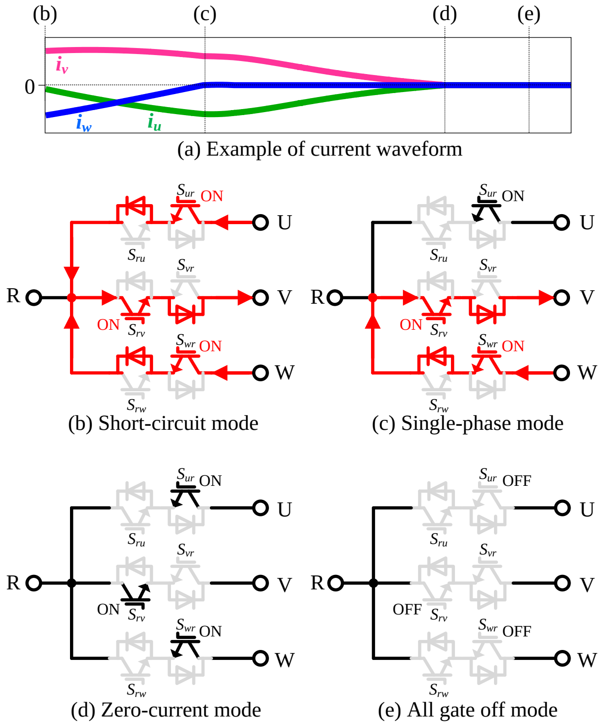


Fig. 6. Output voltage vector of the charging mode and the discharging mode toward the motor current vector in Sequence I.

Table 2. Switching pattern of the voltage source inverter at Sequence I.

	Direction of current			State of switch of inverter					
	i_u	i_v	i_w	S_{pu}	S_{pv}	S_{pw}	S_{nu}	S_{nv}	S_{nw}
Discharge	+	-	-	ON	OFF	ON	OFF	ON	OFF
	+	-	+	OFF	OFF	ON	ON	ON	OFF
	-	-	+	OFF	ON	ON	ON	OFF	OFF
	-	+	+	OFF	ON	OFF	ON	OFF	ON
	-	+	-	ON	ON	OFF	OFF	OFF	ON
	+	+	-	ON	OFF	OFF	OFF	ON	ON
Charge	+	-	-	OFF	OFF	ON	ON	ON	OFF
	+	-	+	OFF	ON	ON	ON	OFF	OFF
	-	-	+	OFF	ON	OFF	ON	OFF	ON
	-	+	+	ON	ON	OFF	OFF	OFF	ON
	-	+	-	ON	OFF	OFF	OFF	ON	ON
	+	+	-	ON	OFF	ON	OFF	ON	OFF



(a) Example of current waveform

(b) Short-circuit mode (c) Single-phase mode

(d) Zero-current mode (e) All gate off mode

Fig. 7. Operational modes in Sequence II of the proposed halt sequence. The matrix converter interrupts the motor current by using the turn-off of the freewheel diode in Sequence II.

the discharging mode. Sequence I ends when the q-axis current reaches zero.

Fig. 7 illustrates Sequence II that is utilized to prevent the snubber capacitor voltage from the rise by circulating the motor current inside the matrix converter. The switching state in the matrix converter turns a short-circuit condition to suppress the rise of the snubber capacitor voltage in Sequence II. The following represents the switching states of the matrix converter. First, the switching pattern of two IGBT in the bi-directional switch is decided corresponding to the direction of current when Sequence II starts. Table 3 shows the switching pattern. For instance, when U-phase current flows to load side as shown in Fig. 7(a), S_{ur} is turned on and S_{ru} is turned off in order not to interrupt U-phase current. U-phase current flows to load side via the freewheel diode of S_{ru} and IGBT of S_{ur}. Similarly, other IGBTs which are connected to R-phase (S_{rv}, S_{vr}, S_{rw} and S_{wr}) are decided corresponding to the direction of current. In addition, the bi-direction switches which are connected to S-phase and T-phase are turned off. Then, the matrix converter is short-circuited as shown in Fig. 7(b). The switching state of the short-circuit mode avoids the regeneration current flowing into the snubber circuit. Then, when one of the three-phase currents reaches zero, the freewheeling diode is turned off automatically as shown in Fig. 7(b). Thus, the matrix converter turns the condition of a single phase mode. Then, the zero-current mode also turns the remaining two freewheel diodes off naturally when the current is zero, severally as shown in Fig. 7(c). Finally, all bi-directional switches are turned off as shown in Fig. 7(d). Therefore, because Sequence II averts the regeneration current

Table 3 Switching pattern of Sequence II.

Direction of current			State of Phase 2					
i_u	i_v	i_w	S_{xu}	S_{ux}	S_{xv}	S_{vx}	S_{xw}	S_{wx}
+	-	-	ON	OFF	OFF	ON	OFF	ON
+	-	+	ON	OFF	OFF	ON	ON	OFF
-	-	+	OFF	ON	OFF	ON	ON	OFF
-	+	+	OFF	ON	ON	OFF	ON	OFF
-	+	-	OFF	ON	ON	OFF	OFF	ON
+	+	-	ON	OFF	ON	OFF	OFF	ON

Table 4 Simulation and experimental condition.

Rated motor power	3.7 kW
Rated motor voltage	180 V_{rms}
Rated current	14.1 A_{rms}
Rated speed	1800 rpm
Number of poles	6 poles
Winding resistance	0.693 Ω
d-axis inductance	6.2 mH
q-axis inductance	15.3 mH
Back-electromotive force	141 V_{rms}@1800rpm
Snubber voltage	283 V
Threshold over-voltage	480 V

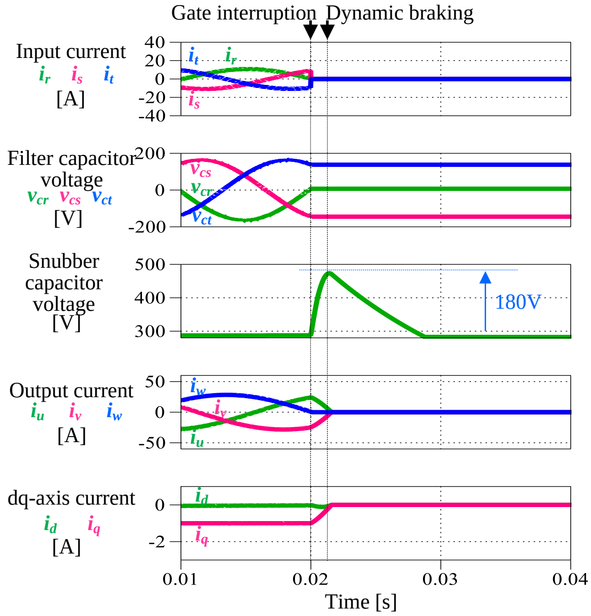


Fig. 8. Simulation result of the gate interruption. After all switches are turned off at the same time, the snubber voltage increases by 180 V

flowing into the snubber capacitor, the suppression of the snubber voltage rise can be achieved.

III. SIMULATION RESULTS

Fig. 8 shows the simulation result of the gate interruption. In the simulation, the magnetic contactor is opened and the gate interruption, which is interrupts the gate signals, turns all switches off simultaneously. In Fig. 8, the snubber capacitor voltage increases by 180 V after the gate interruption. After the snubber capacitor voltage reaches 460 V, the dynamic break circuit is operated to ensure that the snubber voltage do not exceed the designed threshold voltage. The snubber capacitor

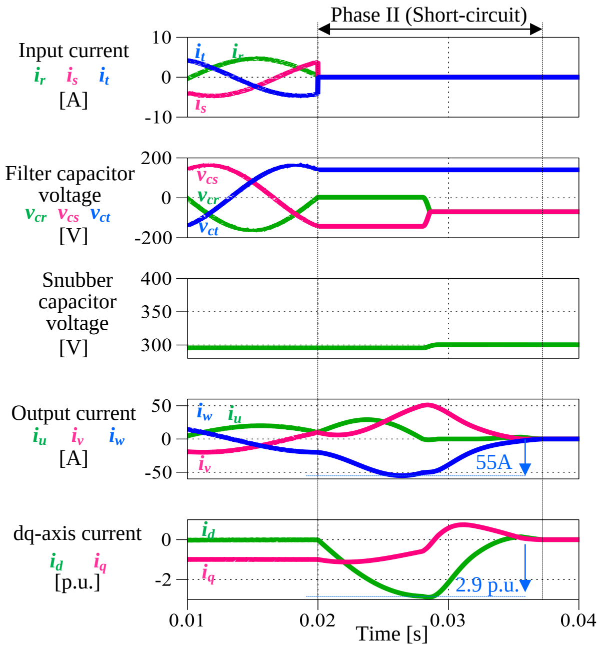


Fig. 9. Simulation result of only Sequence II. The motor current increases to 55A after PMSM is short-circuited.

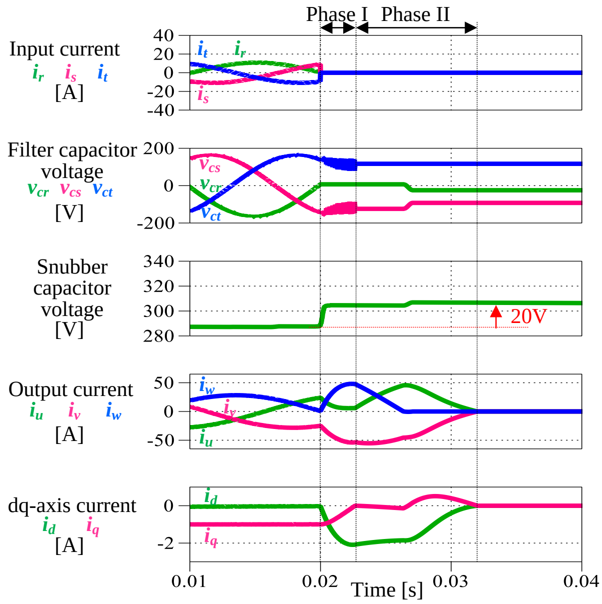


Fig. 10. Simulation result of the proposed halt sequence. The matrix converter interrupts the motor current by the turn-off of the freewheel diode. The fluctuation of the snubber capacitor voltage is suppressed to less than 20V.

voltage is reduced instantly by the brake resistance which consumes the regeneration energy after the dynamic break circuit is operated. The large-capacity resistor to consume the regeneration energy is essential for this method in order to prevent the snubber capacitor from the overvoltage problem.

Fig. 9 shows the simulation result of only short-circuit mode of Sequence II. If the output current of 3.0 p.u. flows in the experimental system, it is possible to cause the burnout and the irreversible demagnetization. In Fig. 9, the motor current increases to 55A because PMSM is short-circuited without Sequence I. Even if the overcurrent protection works, the

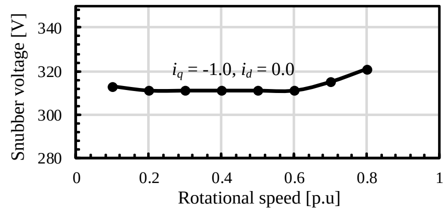


Fig. 11. Snubber voltage rise when PMSM is not the flux-weakening region

Table 5 Experimental condition.

Rated motor power	3.7 kW
Rated motor voltage	180 V_{rms}
Rated current	14.1 A_{rms}
Rated speed	1800 rpm
Number of poles	6 poles
Winding resistance	0.643 Ω
d-axis inductance	7.5 mH
q-axis inductance	15.1 mH
Back-electromotive force	151 V_{rms}@1800rpm
Rated snubber voltage	283 V
Threshold over-voltage	400 V
Filter indactance	2 mH
Filter capacitance	37 μF
Filter resistance	47 Ω
Snubber capacitance	100μF

snubber capacitor voltage rises drastically. Therefore, this method is not practical.

Fig. 10 represents the simulation results of the proposed halt sequence. In Fig. 8, the magnetic contactor is opened at 20 ms. Then, the matrix converter implements the switching patterns in Table 1 and Table 2 depending on the current direction and the input voltage. After the q-axis current reaches zero and PMSM is in the flux-weakening region at approximately 28 ms, Sequence II short-circuits PMSM. From the result, the proposed halt sequence can suppress the motor current to below 2.1 p.u of the rated current. In addition, Sequence I suppresses the rise of the snubber capacitor voltage to below 0.1 p.u. of the rated voltage.

Fig. 11 shows the snubber voltage rise in the speed rigion which does not include the flux-weakening region. The snubber voltage is below 400V when the snubber voltage is larger than the terminal voltage of PMSM below 1523 r/min (= 0.846 p.u.).

IV. Experimental Results

Table 3 shows the detail of the experimental condition. The proposed sequence is implemented in DSP. Therefore, due to the operation switching period of Sequence I, the filter capacitance is large than the general one in this experiment. The d- and q- axis current is calculated by DSP.

Fig. 12 shows the experimental waveform of the gate interruption. In Fig. 12, the snubber capacitor voltage increases by 100 V after the gate interruption. After the gate interruption, the switching device of the dynamic break circuit is turned on. Because the brake resistance is consuming the regeneration energy, the snubber capacitor voltage drops rapidly after the brake register begins consuming the regeneration energy.

Fig. 13 represents the experimental results of the proposed halt sequence. In Fig. 13, the snubber capacitor voltage vibrates during from t_1 to t_2 because the hysteresis control of Sequence I maintains the the snubber capacitor voltage. Sequence II short-circuits PMSM when the q-axis current turns positive at t_2. In addition, the maximum snubber capacitor voltage rises to 45 V during Sequence I. The rise of the snubber capacitor voltage is approximately 50% lesser than Fig. 12. On the other hand, the maximum output current is suppressed to below three times of the rated current. From Fig. 13, it is confirmed that the proposed halt sequence can suppress the rapid voltage rise of the snubber capacitor and the short-circuit current without the dynamic brake circuit.

V. Conclusion

This paper proposes the halt sequence for the matrix converter which suppresses the rising of the snubber capacitor voltage by avoiding the motor current flowing into the snubber circuit. The proposed halt sequence interrupts the regeneration current by using the short-circuit and suppresses the snubber voltage rise without the the additional parts. The proposed halt sequence suppresses the snubber voltage rise within 45V without the dynamic brake circuit in the experiment. The simulation and experimental results demonstrated the effectiveness of the proposed sequence.

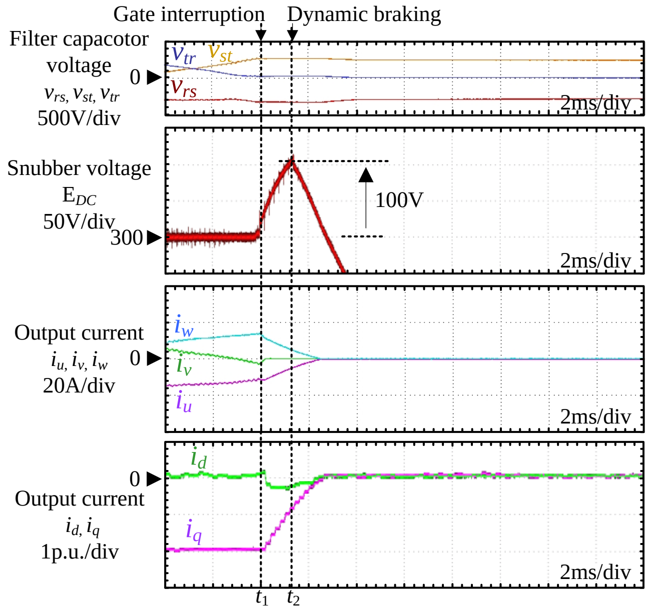


Fig. 12. Experimental results when all gate signals are interrupted as the halt sequence. The snubber capacitor voltage rises by approximately 100 V after the magnetic contactor is opened and all switches are turned off.

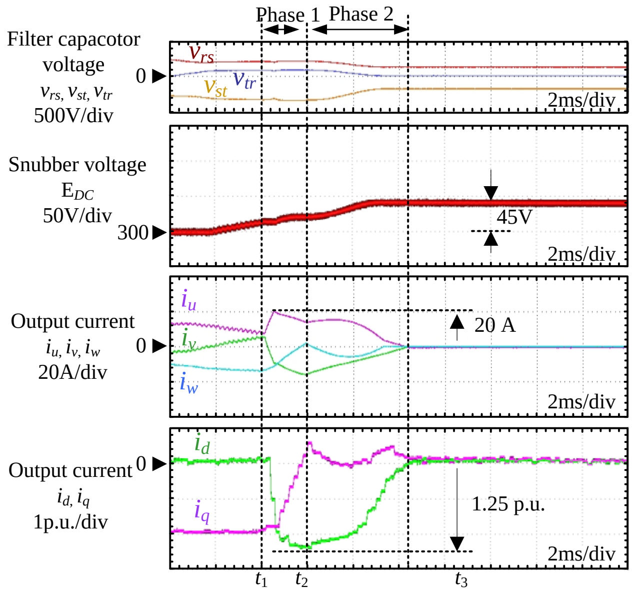


Fig. 13. Experimental results when the proposed halt sequence is applied. It is confirmed that the rise of the snubber capacitor voltage is 45 V during the Sequence I and Sequence II.

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