Surge Voltage Suppression Methods for Three-phase to Single-phase Matrix Converter

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***Abstract*—This paper discusses surge voltage suppression methods in order to design a large capacity three-phase to single-phase matrix converter which is used in AC-DC converters. In order to reduce the surge voltage, the design criteria based on the flow chart of a laminated bus bar (LBB) for the three-phase to single-phase matrix converter is clarified to achieve the lowest stray inductance. As a result, the maximum stray inductance of the LBB for 200-V, 50-kW is achieved to 59 nH in simulation and 58.3 nH in experiment. Besides, when the surge voltage exceeds the tolerance, a snubber capacitor is used in order to limit the surge voltage. In this paper, the design method of the snubber capacitor is also proposed. Concretely, the relationship among snubber capacitance, surge voltage and turn-on loss is derived. As the result, it is confirmed that the surge voltage becomes 231 V when the output current is 310 A by experiment. Thus, the design method of snubber capacitor to suppress the surge voltage is validated.**

Keywords—three-phase to single-phase matrix converter; surge voltage suppression; laminated bus bar; simple AC snubber

I. INTRODUCTION

Three-phase AC-DC converters have been applied in many applications such as telecommunication power system, DC power transmission and quick battery charger for electric vehicle [1-2]. In the three-phase AC-DC converter, an isolated transformer is required in terms of protection and noise elimination. However, the commercial frequency isolated transformer is bulky. In order to solve this problem, a system, which is composed of a PWM rectifier, a PWM inverter and a high frequency transformer, has been discussed [3]. In this system, small transformer is used owing to the increase of the frequency. However, large boost up inductors and an electrolytic capacitor are required.

On the other hand, an AC-DC converter using a three-phase to single-phase matrix converter has been attracted [4-5]. The advantages of matrix converters are as follows: high efficiency, small size and long life-time owing to the absence of boost up inductors and an electrolytic capacitor [6]. However, in comparison with the conventional AC-DC converter, the current loops of the three-phase to single phase matrix converter become longer. This is because the bi-directional switching device, which is unavailable in module, is used with two switching devices. Thus, the surge voltage becomes larger when the three-phase to single-phase matrix converter is applied for large capacity application. In other words, large snubber and protection circuit are required in order to suppress the surge voltage which is dominated by the stray inductance. Therefore, in order to achieve high efficiency and reduced size, it is necessary to decrease the stray inductance of current loops or use the snubber circuit to suppress the surge voltage. For this reason, LBBs, which have low stray inductance owing to the laminated structure of conductors and isolators, has been applied in an inverter [7-10]. However, the LBBs for a matrix converter cannot be easily designed in the same way as an inverter because of bi-directional switching devices. On the other hand, general snubber circuit for matrix converters, which is composed by the diode rectifier, clamped capacitor and discharge resistor, becomes complication structure compared to the inverter due to use of the AC snubber.

In this paper, a design method of LBBs for the three-phase to single-phase matrix converter, which have low stray inductance, is revealed. The design point of LBB for matrix converters is differ to that of the conventional PWM rectifiers and inverters because of the current type converter in the view from input side. In addition, the simple AC snubber circuit, which connects a capacitor with a switching device in parallel, is proposed. This technology becomes important when the surge voltage suppression is needed in order to achieve high power output of several hundred-kW direct AC-AC converters. This paper is organized as follows. First, a LBB is designed to focus on layout of filter capacitor and switching device on current loops which affect surge voltages. Then, in order to evaluate the operation of the LBB, stray inductances and temperature of the LBB are simulated. Second, the snubber circuit, which is composed by a capacitor for a bi-directional IGBT, is evaluated. In particular, the relationship among the snubber capacitance, surge voltage and turn-on loss is theoretically calculated. Next, the validity of the theoretical formulas is validated by switching test. Third, the validity of design of the LBB is confirmed by comparing the experimental result and the simulation results. Finally, the surge voltage is measured by adopting the designed LBB and the designed snubber capacitor. Based on these results, the design method of LBB and snubber circuit is confirmed.

II. Circuit Topology

Fig. 1 shows the circuit configuration of the conventional AC-DC converter. The three-phase AC-AC converter is composed of an input LC filter, boost-up inductors, a PWM rectifier, an electrolytic capacitor and a PWM inverter. The features of the conventional system are as follows: (i) large converter loss owing to many conversion times, (ii) large size and short life-time owing to the electrolytic capacitor and the boost-up inductors, however (iii) the simple snubber circuit for reducing the surge voltage.

Fig. 2 shows the circuit configuration of the AC-DC converter with a three-phase to single-phase matrix converter. The three-phase to single-phase matrix converter can convert three-phase AC into high frequency AC of several-ten-kHz directly. In addition, the three-phase to single-phase matrix converter does not need large passive components such as boost up inductors and an electrolytic capacitor. As a result, the advantages of this system are as follows: (i) high efficiency owing to directly conversion AC into AC, (ii) small size and long life-time owing to absence of an electrolytic capacitor and boost-up inductors. Thus, it is expected that the three-phase to single-phase matrix converter is applied in large capacity applications. In order to apply the three-phase to single-phase matrix converter for large capacity application, it is necessary to suppress a surge voltage with a snubber circuit. However, the conventional snubber circuit, which is composed by a capacitor and a resistor, for each bi-directional switching device leads to increase the loss of the snubber.

III. Surge Voltage Suppression Methods

In order to reduce the size of the snubber and protection circuit, a surge voltage suppression method is discussed in this section. First, the surge voltage V_s occurs when the energy, which is stored in stray inductor l_s, transfers to a parasitic capacitance of switching device C_{CE}. Thus, the surge voltage V_s is expressed as

$$V_s = \sqrt{\frac{l_s}{C_{CE}}} I_{off} \tag{1}$$

where, the turn-off current I_{off} is constant. According to (1), in order to suppress the surge voltage, it is necessary to decrease the stray inductance l_s or increase the capacitance C_{CE}. Thus, this paper discusses two methods in details.

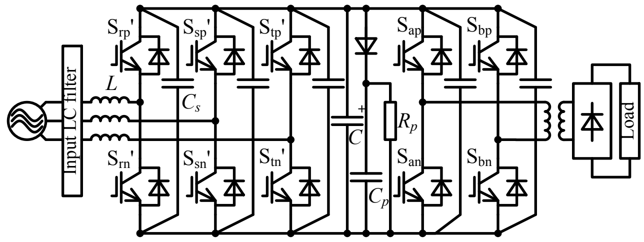


Fig. 1. Configuration of the conventional AC-DC converter

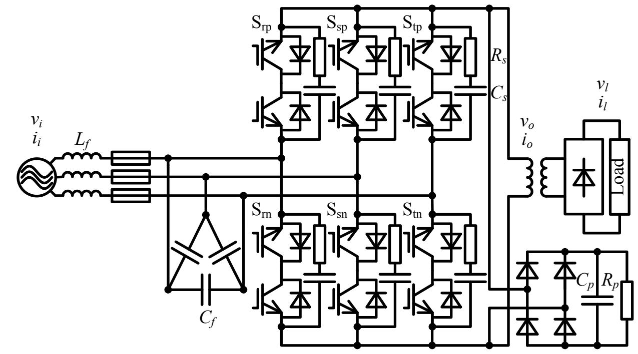


Fig. 2. Configuration of the AC-DC converter with the three-phase to single-phase matrix converter

Fig. 3 shows the flow chart to design the three-phase to single-phase matrix converter for suppression of the surge voltage. First, all components are selected by specification of system in order to design LBBs. Additionally, the voltage and current at worst case are calculated in order to design the surge voltage. Next, the LBB, which has low stray inductance, is designed for the three-phase to single-phase matrix converter. Then, temperature T_{LBB} of the designed LBB is calculated by simulation [11]. If the maximum temperature T_{LBB} is higher than the allowable temperature of the components T_c which are connected with the LBB, it is necessary to modify the design of the LBB. Second, stray inductances l_s of the designed LBB is calculated by simulation [11]. Then, the maximum allowable inductance l_s' is calculated by parasitic capacitance which is obtained by switching test using the selected switching device. It is noted that, in case of $l_s \geq l_s'$, the design of the snubber capacitor C_s, as shown in Fig. 2, is applied because the surge voltage is larger than that of the design value. However, the turn-on loss increases owing to the additional snubber capacitor. Thus, it is necessary to limit the junction temperature T_j to the allowable junction temperature T_j' by redesigning the cooling system.

A. Laminated Bus Bar

In this section, the design method of a LBB for the three-phase to single-phase matrix converter is discussed. In order to design the LBB, it is important to decide the terminal position of all components. Thus, all components are selected based on the specification before the design of LBBs. First, the high frequency transformer is designed the specification which the excitation current is 20% of the rated output current. Second, the cut-off frequency of input LC filter is designed to assure the input ripple current is less than 5% of the rated input current. At first, the input filter capacitance C_f is designed by assuming that the input ripple voltage is 10% of the rated input voltage. Next, the input filter inductance L_f is designed from the cut-off frequency and the filter capacitance C_f. Third, the clamped capacitance C_p of the protection circuit is designed based on the surge voltage which is generated by excitation inductance of high frequency transformer. Moreover, the discharge resistance R_p is calculated by the loss of protection circuit. Furthermore, the snubber diode is selected based on the current squared times at the worst case. It is noted that the amplitude and conduction time of the diode current at the worst case are confirmed by simulation. Next, the switching device is selected based on the maximum switching voltage and current at the worst case. Finally, the loss is analyzed by simulation using loss characteristic of the switching device [12]. Based on the loss analysis result, the cooling system is designed by thermal analysis for heat-sink. Table I lists the specification of the system and Table II lists the selected components for the system.

The design of LBBs for matrix converters is explained. In Fig. 1, LBBs for the PWM rectifier and the PWM inverter are designed to make the loop area, which is composed by the DC link capacitor and the upper and lower arm (S_{rp}', S_{rn}'), become small. On the other hand, in Fig. 2, energy, which is stored in stray inductor in input layers, transfers to parasitic capacitor of switching device owing to resonant circuit which composed by the stray inductor, the input filter capacitor and the parasitic capacitor of the upper or lower arm (S_{rp}, S_{sp}, S_{tp}). Therefore, LBBs for the three-phase to single-phase matrix converter are designed to make six loop areas, in which two bi-directional IGBTs in upper or lower arm are in pair with each input filter capacitor, become small.

Fig. 4 shows the configuration of two designed LBBs for the three-phase to single-phase matrix converter and current loop at the maximum stray inductance. It is noted that the difference between Fig. 4(a) and (b) is the direction of the switching devices. In Fig. 4(a), the switching device is arranged by assuming that the distance among each terminals of switching device becomes short. On the other hand, in Fig. 4(b), the distance between each terminals of switching device becomes longer than that of Fig. 4(a). This is because the switching devices rotate 90 degrees for an angle of switching device in Fig. 4(a) in order to improve performance of cooling system. As a result, the maximum stray inductance in Fig. 4(a) and Fig. 4(b) is calculated to 59 nH and 65 nH by simulation, respectively. Thus, the configuration of the LBB in Fig. 4(a) is adopted because the maximum stray inductance of Fig. 4(a) is lower than Fig. 4(b).

Fig. 5 shows the thermal simulation result of the LBB of Fig. 4(a). The current in simulation condition is the rated current of three-phase to single-phase matrix converter i.e. the current of the input layers is 50 Hz and 144 A, and the current of the output layers is 10 kHz and 202 A. Thus, the current density of the output layers is higher than the input layers. As a result, the temperature of the output layer trends to be higher than the input layer. Additionally, the maximum temperature of the LBB T_{LBB} is 54 °C when ambient temperature is the worst case 40 °C because terminal for switching device is narrow. Therefore, the maximum temperature 54 °C is lower than the allowable temperature of all components 85 °C is confirmed.

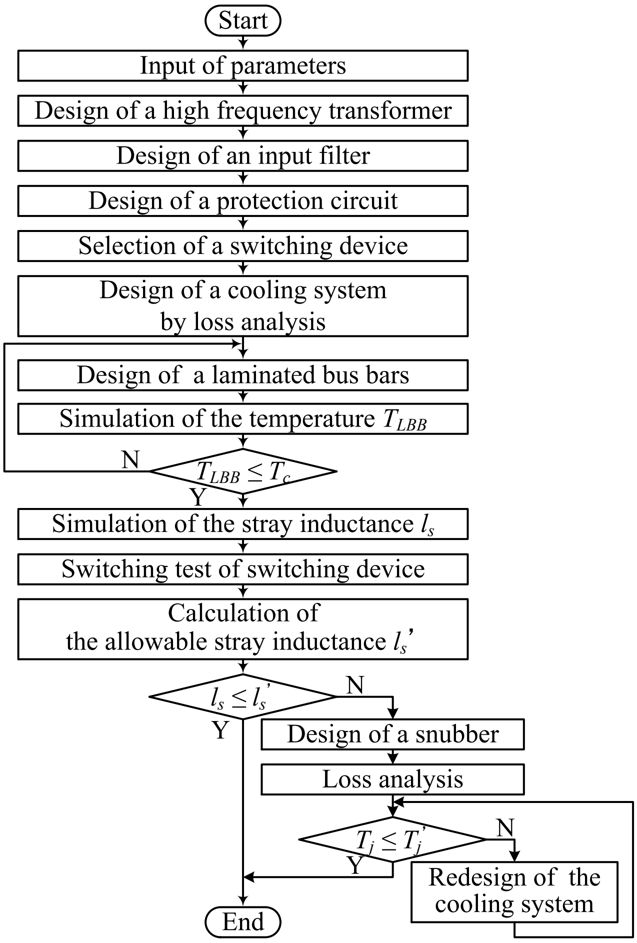


Fig. 3. Flow chart to design the three-phase to single-phase matrix converter for suppression of the surge voltage

TABLE I. SPECIFICATION OF THE SYSTEM

Item		Symbol	Valu
Input	voltage	V_i	200V(±10%)
	frequency	f_i	50 or 60Hz
	power factor	cosφ	≥0.95
	current THD	THD_i	≤ 5%
	ripple voltage	V_r	28.2V
Load	voltage	V_l	500V
	output power	P_l	50kW
Switching frequency		f_s	10kHz
Ambient	temperature	T_a	-10~40°C
	altitude	A_a	≥1000m

TABLE II. SELECTED COMPONENTS FOR THE SYSTEM

Part	Symbol	Calculated value	model number of device	Maximum ration
IGBT	$S_{(rst/pn)}$	-	MITSUBISHI "CM400C1Y-24S"	1200V 350A
Heat sink	-	-	MERSEN "MF250T13A80AF32D"	-
Fan	-	-	SUNON "PMD1204PPB1-A"	26.5cfm
Input filter capacitor	C_f	160μF	Cornell-Dubilier "944U161K801ABM"	$230V_{ac}$
Input filter reactor	L_f	10μH	STS induktivitaeten	350A
Protection diode	-	-	IXYS "DSEI2X30-12B"	1200V 28A
Protection capacitor	C_p	2.2μF	EPCOS "B32656S8225J561"	$850V_{dc}$
Protection resister	R_{p1}	47kΩ	TE Connectivity "YP1047KJ"	825V 10W
	R_{p2}	10kΩ	Arcol "HS100 10K J"	1900V 100W

B. Simple AC Snubber Circuit

In order to limit the surge voltage to the design value, the simple AC snubber circuit, which connects a capacitor in parallel, is adopted when the maximum stray inductance by simulation is larger than the allowable stray inductance. However, the snubber capacitor C_s increases the turn-on loss E_{on} because a short current flows at turn-on by the snubber capacitor. Accordingly, the switching device is broken owing to large current. Therefore, in terms of the surge voltage and the switching loss, it is important to design C_s. In addition, an adjustment of gate resistance also suppresses the surge voltage. However, adjustment of dv/dt is limited by gate resistance in recent IGBTs. Additionally, the surge voltage suppression by gate resistance leads to increase the both turn-on loss and turn-off loss. Owing to this, an adjustment of gate resistance for the suppression of surge voltage is not considered.

Fig. 6 shows the test circuit for evaluating the snubber capacitor. It composes the buck chopper. It is noted that the upper switching device S_p is always on-state. On the other hand, the lower switching device S_n is switched. The surge voltage V_s and turn-on loss E_{on} are evaluated from the measured voltage and current of the lower switching device S_n, and the relationship between each C_s. Thus, V_s is expressed as

$$V_s = \sqrt{\frac{2l_s}{C_{CE}+C_s}} I_{off} = \sqrt{\frac{C_{CE}}{C_{CE}+C_s}} V_{s0} \qquad (2)$$

where, I_{off} is the current at turn-off, V_{s0} is the surge voltage without snubber capacitor. It is noted that C_{CE} is previously measured by switching tests. According to (2), surge voltage V_s can be suppressed by increasing C_s. On the other hand, energy, which is stored in a capacitor, transfers E_{on}. Thus, E_{on} is expressed as

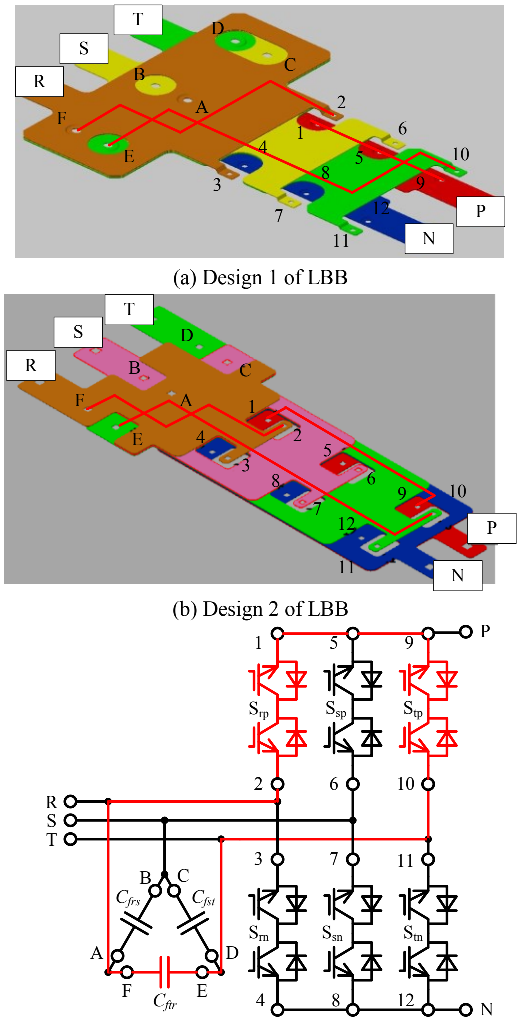
$$E_{on} = \frac{1}{2}(C_{CE}+C_s)V_{on}{}^2 = \frac{C_{CE}+C_s}{C_{CE}} E_{on0} \qquad (3)$$

where, V_{on} is the voltage at turn-on, E_{on0} is the turn-on loss when the snubber capacitor is not connected.

Fig. 7(a) shows the switching waveform at turn-off when the snubber capacitor C_s is not connected. The surge voltage V_{s0} is 96 V when the turn-off current I_{off} is 11 A. In Fig. 7(b), the surge voltage V_s is reduced to 26 V because the snubber capacitor C_s of 50 nF for the parasitic capacitor C_{CE} of 4.21nF is connected.

Fig. 8(a) and (b) show the switching waveform at turn-on. In Fig. 8(a), the turn-on current I_{on0} is 18.8 A when the snubber capacitor is not connected. In Fig.7(b), the turn-on current I_{on} is increase to 74.8 A because of the short current owing to the snubber capacitor C_s of 50 nF for the parasitic capacitor C_{CE} of 4.21 nF.

Fig. 9 shows the surge voltage and turn-on loss characteristics based on C_s and C_{CE} by the experiment. It is noted that the sum of C_{CE} and C_s was normalized by C_{CE}. In addition, V_s and E_{on} are normalized by switching voltage



(a) Design 1 of LBB

(b) Design 2 of LBB

(c) Maximum inductance loop

Fig. 4. LBB for the matrix converter

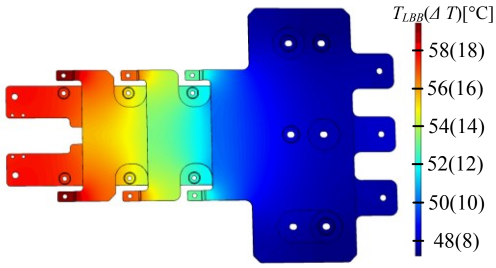


Fig. 5. Temperature T_{LBB} of the Fig .4(a) LBB
The ambient temperature is 40 °C.

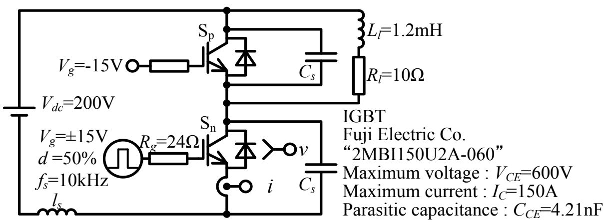
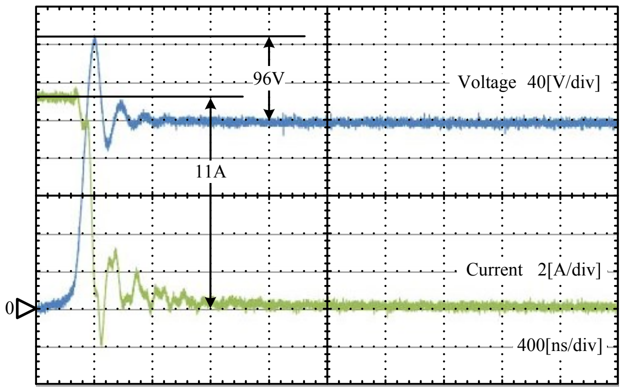
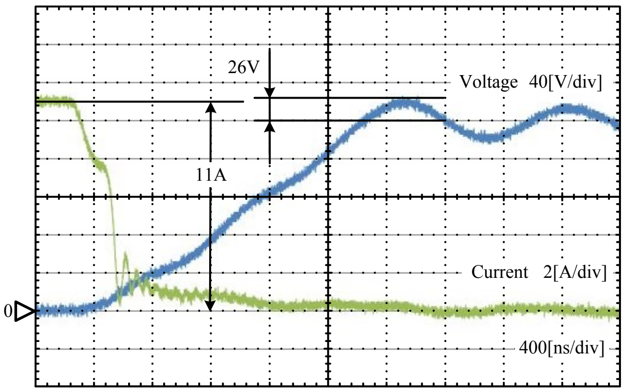


Fig.6. Test circuit for evaluating the snubber circuit

$V_{on(off)}$, current $I_{on(off)}$ and V_{s0} or E_{on0}. As the result, the experimental results are almost agreed with the theoretical value. However, the experimental results of V_s and E_{on} are

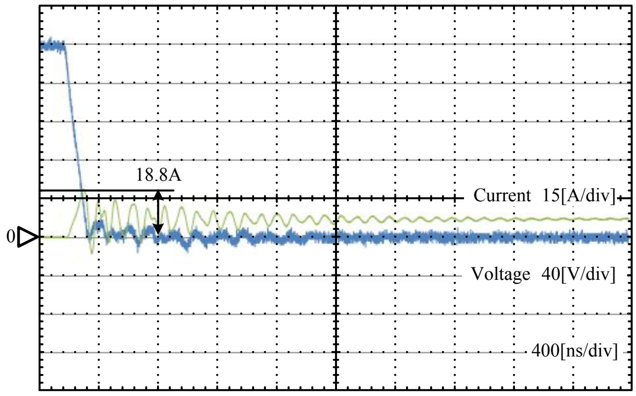


(a) Without snubber capacitor

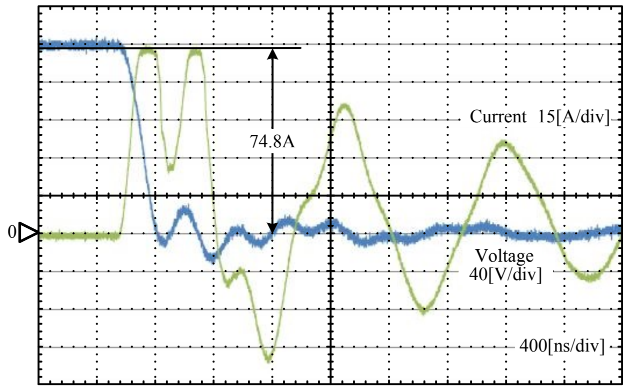


(b) With C_s of 50 nF for C_{CE} of 4.21nF

Fig. 7. Switching waveform at turn-off



(a) Without snubber capacitor



(b) With C_s of 50 nF for C_{CE} of 4.21nF

Fig. 8. Switching waveform at turn-on

lower a little than the theoretical value. This is because all energy, which is stored in stray inductor, is not transferred into the capacitor of the switching device owing to the interconnection resistance and the switching loss. Therefore, the required snubber capacitance to suppress the surge voltage at the worst case is designed by (2).

IV. Experimental Results

A. Evaluation of the Laminated Bus Bar

In this section, the stray inductance and temperature rise of the LBB, which is shown in Fig. 4(a), is evaluated by experiment. First, the stray inductance is measured by switching tests with the LBB.

Fig. 10 shows an example of the test circuit for measuring the stray inductance of the designed LBB. It is noted that the circuit model considers parasitic capacitor and stray inductance. It composes the buck chopper. Additionally, the upper switching device S_p is always on-state, and the lower switching device S_n is switched in the same way as the experiment of evaluating the snubber capacitor. The surge voltage V_s and the turn-off current I_{off} are measured. Then, the stray inductance on the current loop l is derived by (4).

$$l = \frac{2C_f C_{CE}}{C_f + 2C_{CE}} \left(\frac{V_s}{I_{off}} \right)^2 \tag{4}$$

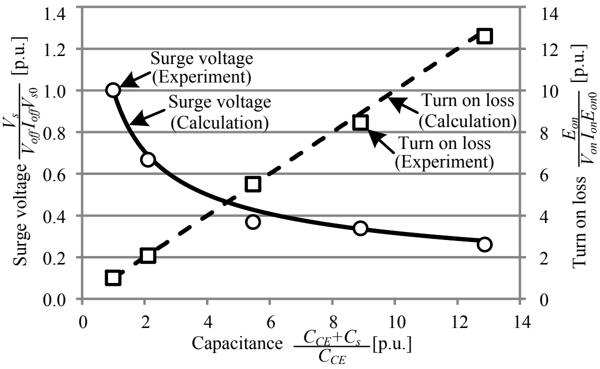


Fig. 9. Surge voltage and turn-on loss characteristics based on capacitance by experiment

where, the stray inductance on the current loop l is sum of the stray inductance of the LBB l_s and the equivalent series inductance (ESL)of the input filter capacitor l_C and the IGBT l_{IGBT}. Therefore, the stray inductance of the LBB l_s is derived by (5).

$$l_s = l - \left(l_C + l_{IGBT} \right) \tag{5}$$

Fig. 11 shows the stray inductance comparison between the simulation and experiment. As the results, it is confirmed that the stray inductance is minimum value when the distance between each input layer and the distance of switching devices S_{rn} and S_{sn} from the filter capacitor C_{frs} are minimum. Moreover, the stray inductance error between the simulation and experiment is 4.8%. This error is because all energy, which is stored in stray inductor, is not transferred into the parasitic capacitor of the switching device owing to the interconnection resistance and the turn-off loss and the values of the parasitic capacitors are not constant. It is noted that the measured surge voltage is dominated by the stray inductance of the LBB and an ESL of the filter capacitor and the IGBT module on the current loop. For this reason, in order to suppress the surge voltage, the switching device and capacitor, which have low ESL, should be selected.

Next, the validity of the temperature rise simulation of LBB is revealed by experiment.

Fig. 12 shows the test circuit for analysis of temperature rise of the LBB. It is noted that the diode was used instead of the switching device. In addition, the current is adjusted by using slid regulator assuming that the root mean squared value of current is the current which the three-phase to single phase matrix converter operates at rated condition.

Fig. 13 shows the analysis result of the temperature of the LBB by the experiment. As the result, the temperature of the LBB agrees with the simulation result. However, the temperature of the LBB around terminal in experiment is a little higher than the simulation result. This is because the interconnection, screw and fuse become the heat sources. On the other hand, the temperature of the LBB except terminal in experiment is a little lower than the simulation result. This is because the ambient wind velocity is ideally 0 m/s and the convection by generation of heat is not considered in simulation.

B. Evaluation of the Simple AC Snubber Circuit

The snubber capacitor is designed based on the measured maximum stray inductance by experiment. Furthermore, the suppression effect of the surge voltage is evaluated using the snubber capacitor by assuming the current at the worst case. It is assumed that the maximum surge voltage is 60% of the worst case voltage of switching device or less. In this paper, the capacitor of 50 nF is connected. In addition, the designed value of the surge voltage is 359 V at the worst case.

Fig. 14 shows the switching waveforms at turn-off on the each loop. From Fig. 14(a), (b) and (c), it is confirmed that the surge voltage on the loop V, which is shown by Fig. 11, is the largest when the turn-off current is same value. This is because the stray inductance of the LBB on loop V is the largest in all loops. Accordingly, the surge voltage becomes 231 V when the output current is 310 A on the loop V. The measured value is smaller than the designed value. This is because all energy, which is stored in stray inductor, is not transferred into the capacitor of the switching device owing to the interconnection resistance and the switching loss. Thus, the surge voltage is lower than design value. Therefore, the design method of snubber capacitor to suppress the surge voltage can be validated.

V. CONCLUSIONS AND FUTURE WORKS

This paper proposed the methods of the surge voltage suppression in order to design a large capacity three-phase to

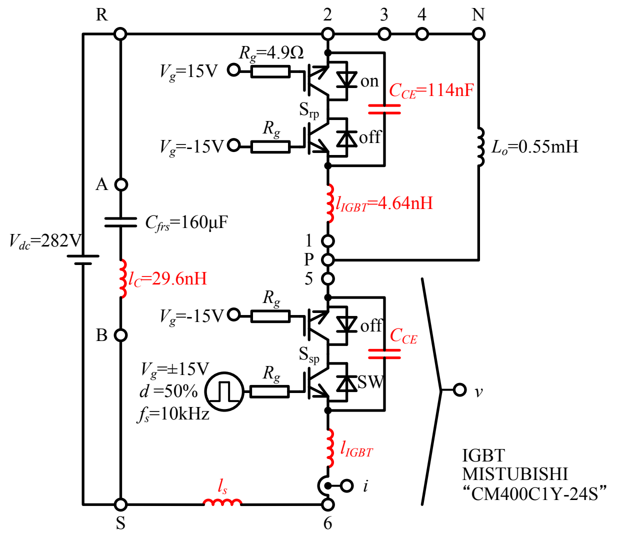


Fig. 10. An example of the test circuit for measuring the stray inductance of the designed LBB

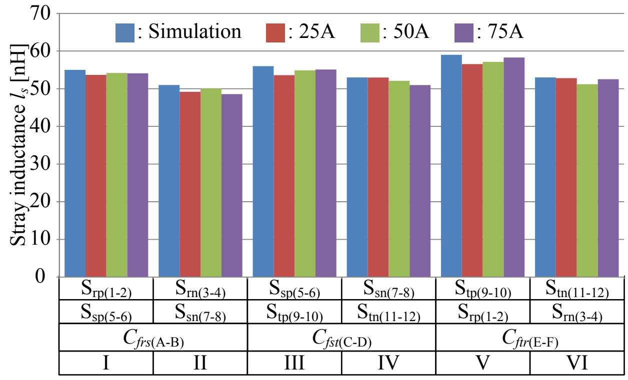


Fig. 11. Stray inductance comparison between the simulation and experiment
I to VI are number of the current loop which affect surge voltages.

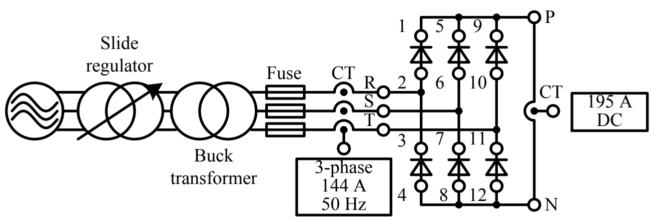


Fig.12. Test circuit analyzing temperature rise

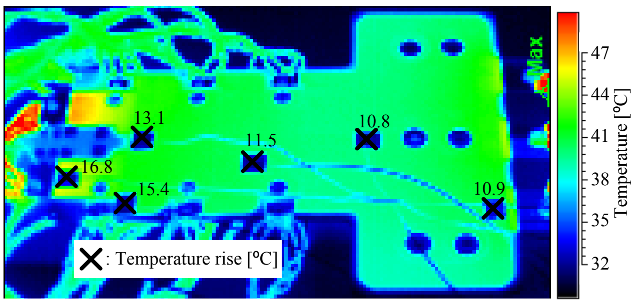


Fig. 13. Experimental result of temperature rise of the LBB
The ambient temperature is 26 °C.

single-phase matrix converter which is used in AC-DC converters. In order to suppress the surge voltage, it is necessary to reduce the stray inductance. Thus, the LBB, in which layout of components and laminating layer is considered by assuming that current loop to affect surge voltage, was designed. As the result, it was confirmed that the maximum stray inductance was 59 nH in simulation and 58.3 nH in experiment.. On the other hand, the surge voltage can be reduced by adopting the snubber circuit which connects a capacitor for a switching device. Thus, the snubber capacitor was designed and evaluated by experiment. As the result, the relationship among C_s, V_s and E_{on} was revealed. Thus, it was confirmed that the snubber capacitor can be designed by on-time switching test in which parasitic capacitance of switching device is measured. Finally, the surge voltage can be suppressed to design value or less by adopting the designed LBB and snubber capacitor. Based on these results, the three-phase to single-phase matrix converter can be applied for 50-kW system.

In future work, the stray inductance and temperature rise of the LBB and surge voltage will be evaluated when the three-phase to single-phase matrix converter is operated at rated power.

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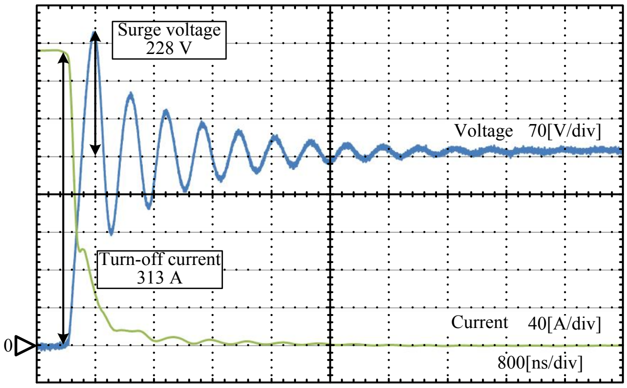
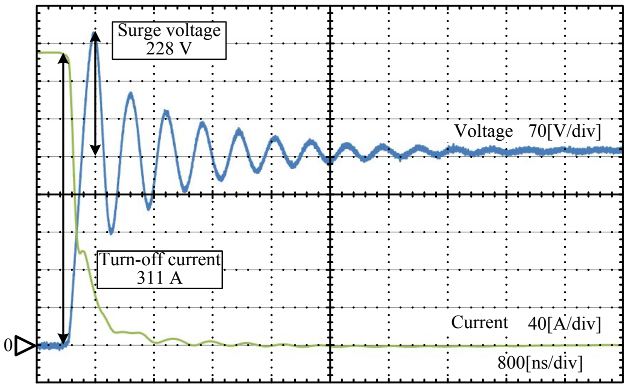
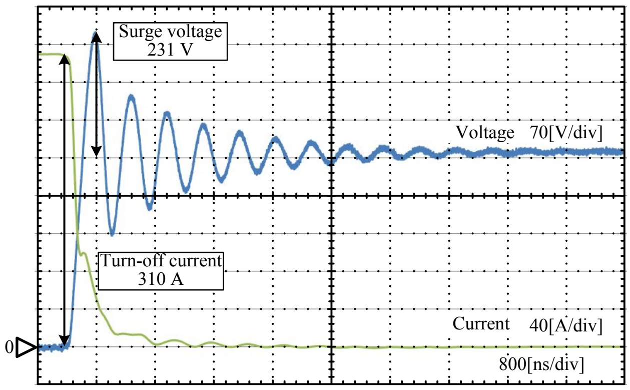


(c) Loop I which is composed of S_{rp}, S_{sp} and C_{frs}



(b) Loop III which is composed of S_{sp}, S_{tp} and C_{fst}



(c) Loop V which is composed of S_{tp}, S_{rp} and C_{ftr}

Fig. 14. Switching waveform at turn-off

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