Experimental Verification of Conduction Noise of Three-level V-connection Rectifier-Inverter System

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***Abstract*— This paper discusses the conduction noise reduction possibility of a transformer-less three-level V-connection rectifier-inverter system. This circuit is used for the main circuit in an Uninterruptible Power Supply (UPS) system. The efficiency of this circuit is higher than that of the conventional three-phase rectifier-inverter circuit due to no isolated transformer in output side. In this paper, to verify the conduction noise of the V-connection system, a theoretical analysis about the common-mode currents which based on the common-mode equivalent circuit, is discussed. Based on this, the comparison of the conduction noise between the three-level V-connection Back To Back (BTB) system and the conventional three-level three-phase connection BTB system is assumed. In addition, the conduction noise of two systems are measured and compared in order to confirm the assumption. As a result, it is confirmed that the conduction noise which is generated from the three-level V-connection rectifier-inverter circuit is higher than that of the conventional three-phase rectifier-inverter circuit.**

Keywords*— Multilevel converter, V-connection rectifier-inverter, conducted emission, leakage current

I. Introduction

In recent years, due to the rapid development of the information society, the demand of Online Uninterruptible Power Supply (UPS) has been increasing. UPS which ensures the stability of the power supply and avoids data loss due to power failure, has been applied in many server system all over the world [1-2]. However, in this kind of system, the isolation transformer is required at the output side, which accounts for about 40% of the UPS total weight. Furthermore, the utility of the isolation transformer increases the size of UPS. In addition, the isolation transformer causes the constant loss which lowers the power conversion efficiency [3].

In order to solve above problems, many methods has been proposed [2-4]. One of those is the concept of the transformer-less two-level V-connection BTB system [3-4]. In this system, by grounding the common phase, it is possible to remove the isolation transformer. As a result, high efficiency and miniaturization of UPS can be achieved. However, the DC link voltage in the V-connection BTB system becomes two times higher than that in the three-phase connection BTB system. As a result, high voltage switching devices are required. In order to solve this problem, the three-level V-connection BTB system has been proposed [3]. Compared with the two-level system, the number of the switching devices is increased. However, due to the characteristic of the multi-level circuit, the voltage applied across the switching devices become 1/(n-1) times of the DC link voltage. Here, n is the number of level of the circuit. Therefore, low voltage rating devices can be applied.

On the other hand, it is confirmed that the efficiency of the three-level V-connection BTB system can be improved by 7.9% compared with the three-phase connection BTB system [4]. However, because of the main circuit of UPS, the evaluation of the conduction noise which is generated by the three-level V-connection BTB system is necessary. Hence, the measurement and comparison of the conduction noise between the three-level V-connection BTB system and the conventional three-level three-phase connection BTB system must be conducted. In this case, the conduction noise is evaluated by the conducted emission which transmits in the power line. Therefore, based on Standard CISPR 22, the conducted emission in frequencies from 150 kHz to 30 MHz is measured and evaluated.

The V-connection BTB system has many advantages in terms of the efficiency improvement and size reduction. However, it seems that the conducted emission of the V-connection three-level inverter has not been reported in past works. Especially, the behavior of the neutral point voltage of the V-connection three-level inverter has not been discussed compared with three-phase three-level inverter. In addition, the conventional method to evaluate the conducted emission of the power converter system is measuring the conducted emission and reproducing it by simulation [5-8]. In this method, the simulation results can reproduce the experimental results fairly exactly in the simple systems. However, it does not clarify the reason of the generation of the common-mode voltage. Therefore, the mechanism of the generation of the common-mode voltage is not clear. Hence, it causes difficulties in finding out the method to reduce the conducted emission of the system by suppressing the common-mode voltage.

In this paper, in order to reveal the behavior of the conducted emission of the V-connection three-level BTB system, a theoretical analysis about the common-mode currents which based on the common-mode equivalent circuit, is discussed compared with the three-phase three-level BTB system. The neutral point potential variation of both systems is investigated and formulated in order to clarify the generation of the common-mode voltage. Note that the common-mode voltage is the source of the common-mode current in the system. Moreover, the common-mode current dominates the conducted emission. Hence, based on this analysis, the comparison result of the conducted emission between the three-phase connection BTB system and the V-connection BTB system can be assumed. After that, the experimental results of the common mode leakage current and the conducted emission in two systems are demonstrated. Due to the measurement results, the assumption about the comparison results of the conducted emission between two systems is confirmed.

II. Main Circuit Configuration and Control Strategy

Fig. 1 shows the circuit diagrams of a three-level three-phase connection BTB system, and a three-level V-connection BTB system, respectively. In order to obtain the same output voltage, the DC voltage of the three-level V-connection BTB system is set to two times higher than that of the three-phase connection BTB system. Therefore, in the three-level V-connection BTB system, high voltage switching devices are required. However, in this paper, the same voltage rating switching devices are applied in both systems in terms of the comparison of the conducted emission performance depending on the circuit topology. In addition, the same switching frequency is applied regardless of the connection method.

Fig. 2 shows the control block diagram of the rectifier unit in three-level V-connection BTB system. The rectifier unit is controlled by the Automatic Current Regulator (ACR) and the Automatic Voltage Regulator (AVR) to obtain the sinusoidal input current and to regulate the DC link voltage. In order to obtain the high input power factor, the phase references of the current command value of the ACR are calculated from the input voltage phases. On the other hand, the inverter unit is controlled by open-loop, and the modulation scheme is unipolar PWM modulation, which has the carrier changes between 0 and a positive peak, while the reference is always positive [3]. In the three-phase connection BTB system, the control strategy of the rectifier unit is the same as the V-connection BTB system. However, the current command value of the S phase is derived from the current command value of R phase and T phase by (1).

$$i_s^* = -(i_r^* + i_t^*) \quad (1)$$

where i_r^*, i_s^*, i_t^* are the input current commands.

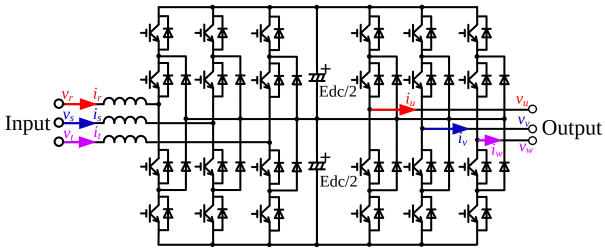
When carrying out the experiment, in order to change from the three-phase connection BTB system to V-connection BTB system, the PWM signal which control the ON / OFF state of the switch of S phase and V phase module in the three-phase connection BTB system, will be set to OFF state.

III. Evaluation Systems

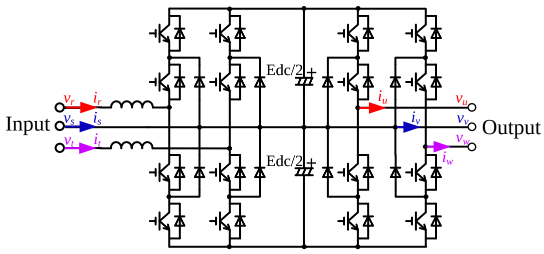
A. Configuration of evaluation system

Fig. 3 shows system configuration to evaluate the conducted emission and the places to observe the common-mode leakage current. These systems are built for simulating the circuit of the UPS. Therefore, there are two EMC filters at the input and output to restrain the EMI noise which is generated from the switching of the main circuit. In addition, an output Low-pass Filter (LPF) is put in order to obtain the sinusoidal waveform. The leakage inductance of the output transformer is used as the filter L in the LPF.

Fig. 3(b) shows the V-connection BTB system. It also has two EMC filters at the input and output, and a LPF at the output. However, in the V-connection system, an inductor



(a)Three-level three-phase-connection BTB system



(b)Three-level V-connection BTB system

Fig.1. Main circuit configuration, which has the PWM rectifier unit at the input and the PWM inverter unit at the output (BTB system)

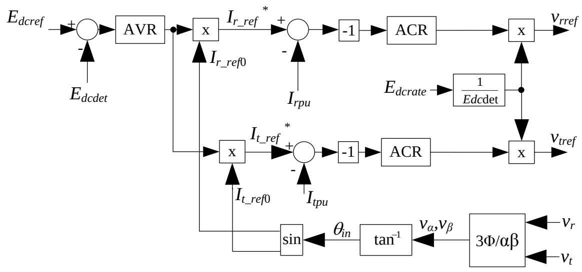


Fig.2. Control block diagram for three-level V-connection rectifier-inverter. It consists of AVR (to control the DC link voltage) and ACR (to control the input current)

which has a same inductance of the leakage inductance of the transformer in the three-phase connection BTB system is needed as the filter L. Note that $i_{CM\_heatsink}$ is the leakage current from the heat sink, i_{CM_output} is the leakage current of the output EMC filter, i_{CM_input} is the leakage current of the input EMC filter, and i_{CM_LISN} is the leakage current which flows into Line Impedance Stabilization Network (LISN).

In addition, it is important to achieve the same stray capacitances between the heat sink and switching devices regardless of the connection method. Therefore, when changing the connection method from three-phase connection to V-connection, the common phase (S phase and V phase) is connected to the neutral point of electrolytic capacitor, and switching devices of the common phase (S phase and V phase) are always turned off.

Fig. 4 shows the circuit configuration of the EMC filter. The EMC filter has three parts: X capacitor, Common Mode Choke (CMC) and Y capacitor. The X capacitor is used to suppress the Differential Mode (DM) current, while CMC and Y capacitor is used to suppress the Common Mode (CM) current. In addition, the design of EMC filter is based on Ref.[12]. Here, the X capacitor's capacity is designed based on an allowable lead angle of current φ because it reduces the power factor at the light load [12]. In addition, the Y capacitor's capacity is designed based on the acceptable leakage current [12].

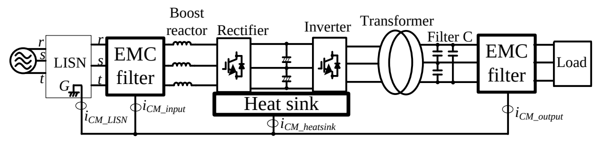
B. Common-Mode equivalent circuit

Fig. 5 shows the equivalent circuit for the common-mode voltage and current of both systems. Note that the polarity of the rectifier common-mode voltage v_{rec} is opposite to that of the inverter common-mode voltage v_{inv} [11]. Next, L_{L1} and R_{L1} are the CM inductance and resistance values of the boost reactor on the input side of the three-phase connection inverter, while L_{L2} and R_{L2} are the CM inductance and resistance values of the V-connection inverter. Note that there is unbalance between the values of L_{L1}, R_{L1} and L_{L2}, R_{L2}. It is because in the three-phase connection BTB system, there are three boost reactors on the input, while there are just two boost reactors in the V-connection BTB system. In addition, R_{load} and L_{load} are the CM inductance and resistance values of the RL load. Here, it can be considered LISN as the parallel circuit of L_1, C_1 and R_1. In addition, the voltage which appears across R_1 is the conducted emission voltage. Furthermore, C_{GH1}, C_{GH2} and C_{GH3} are the parasitic capacitances between the IGBT modules and the heat sink [8]. They are measured between three output terminals of the IGBT modules and the heat sink. Moreover, L_{EMC1}, R_{EMC1} are the inductance and resistance of the input CMC, while L_{EMC2}, R_{EMC2} are the inductance and resistance values of the output CMC. Finally, L_{GH}, L_{GF1}, L_{GF2} are the stray inductances of the grounded lines, while C_{GL}, C_{GTrans} are the stray capacitances of the load and the isolation transformer.

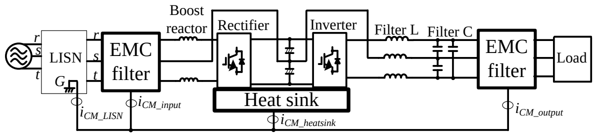
From Fig. 5, it can be known that there are many CM current loops which flow around in the systems. However, for simplicity, only the CM currents which flow through the LISN are considered, because the voltage of this resistance is used to analyze the conducted emission of the system. Therefore, there are three CM leakage currents which are considered in this case:

- Loop 1 : Generated from inverter → Output filter L → stray capacitance of transformer C_{trans} (or not in V-connection) // Output EMC filter // Load → Output EMC filter grounded line → input EMC filter // LISN → rectifier → inverter
- Loop 2 : Generated from rectifier → Boot reactor → input EMC filer // LISN → Heat sink grounded line → Stray capacitance between IGBT modules and heat sink C_{GH2} // $2C_{GH3}$ // C_{GH1} → rectifier
- Loop 3 : Generated from inverter → Stray capacitance between IGBT modules and heat sink C_{GH2} → Heat sink grounded line → input EMC filter // LISN → Boost reactor → rectifier → inverter

From 3 loops above, it can be considered that the input EMC filter plays an important role in bypassing the CM current which flows out the power supply, while the output EMC filter only bypasses the CM current which flows to the load. In addition, it can be known that the stray capacitor of the IGBT modules C_{GH1}, C_{GH2}, C_{GH3} and the stray inductance of the grounded line of heat sink L_{GH} play an important role in the generation of many CM leakage currents. It is because if not



(a)Three-level three-phase-connection BTB system



(b)Three-level V-connection BTB system

Fig.3. Circuit diagram when measuring conducted emission, which use common main circuit for both systems

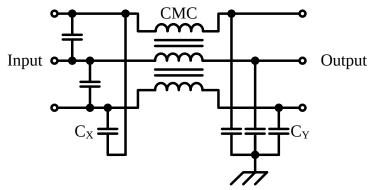


Fig.4. EMC filter

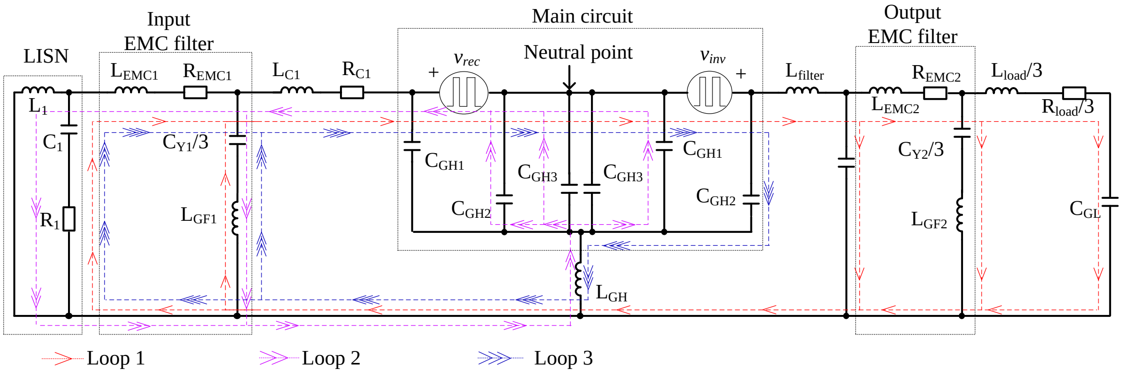
grounding the heat sink, there is only one loop of the CM leakage current which exists in the CM equivalent circuit.

Compared Fig. 5(a) to Fig. 5(b), it can be seen that there is unbalance between three-phase connection BTB system and V-connection BTB system: in the three-phase BTB connection system, there is a stray capacitor of isolation transformer C_{GTrans} on the output side while there is not a similar component in the V-connection BTB system. However, this unbalance is negligible because the impedance of C_{GTrans} is always much larger than the impedance of the output EMC filter connected in parallel to the load.

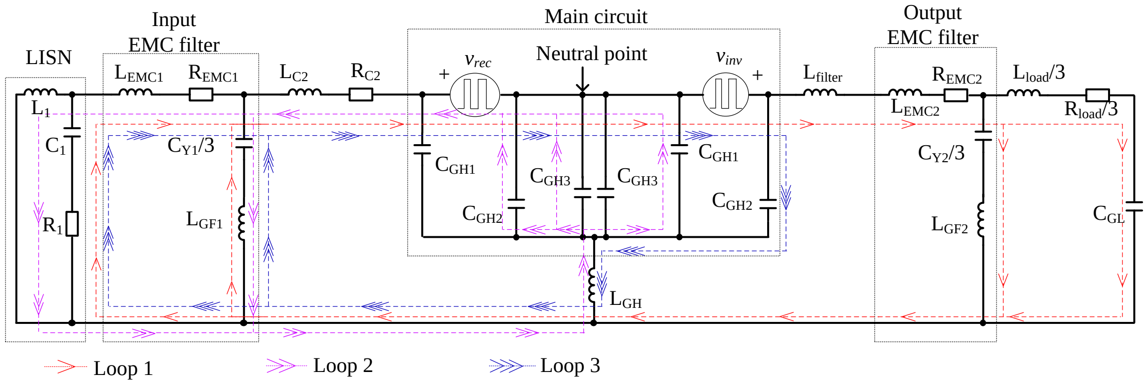
IV. Neutral Point Potential Variation

From the CM equivalent circuit, it can be considered that the CM voltage current paths and stray components are similar in both systems. Therefore, the difference in the magnitude of the CM leakage currents between two systems will be caused by the difference in the magnitude of the CM voltage source v_{rec} and v_{inv}. Note that v_{rec} is the CM voltage between the neutral point of the power supply and the neutral point, while v_{inv} is the CM voltage between the neutral point of the load and the neutral point. Based on this, the analysis of the neutral point potential variation in both systems is necessary. Because of the symmetric of the BTB system, only the analysis of the generation of v_{inv} is needed for discussion. The analysis of the generation of v_{rec} is similar.

Only two of the four switches of one phase are turned on, and connect the output terminal to one of three switching states: Positive (output voltage = $+E_{dc}/2$), Zero (output voltage = 0), Negative (output voltage = $-E_{dc}/2$). Using switching function S_u, S_v, S_w to represent the switching state of each phase U, V, W. In this case, S_u, S_v, S_w can only have one of three values {1, 0, -1} at any time. Here, the switching state variables S_u, S_v, S_w =1 when the output terminal of the corresponding phase is connected to swiching state Positive; S_u, S_v, S_w =0 when connected to switching state Zero and S_u, S_v, S_w



(a). Three-phase connection BTB system



(b). V-connection BTB system

Fig.5. Common-mode equivalent circuit in both systems, the leakage inductance of the isolation transformer in the three-phase connection is replaced by filter L in the V-connection

= -1 when connected to switching state Negative. Thus, the neutral point potential variation v_{nOUT_MP} of the three-phase connection can be caculated by

$$v_{nOUT\_MP} = \frac{E_{dc\_threecon}}{6}(S_u + S_v + S_w) \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where $E_{dc\_threecon}$ is the DC link voltage of the three phase connection inverter.

Similarly, in the V-connection inverter, it can be considered that the switching state variable of V phase is always equal zero i.e. S_v =0, and the DC link voltage E_{dc_Vcon} = $2E_{dc\_threecon}$. Hence, (2) can be rewritten as

$$v_{nOUT\_MP} = \frac{E_{dc\_Vcon}}{6}(S_u + S_w) \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Based on (2), it can be considered that in the three-phase connection inverter, the maximum value of the neutral point potential variation v_{nOUT_MP} = $E_{dc\_threecon}/2$ when the switching state of all three phases is Positive. In addition, based on (3), in the V-connection inverter, it can be considered that the maximum value of the neutral point potential variation v_{nOUT_MP} = $E_{dc\_Vcon}/3$ when the switching state of all two phases is Positive. Because the DC link voltage of the V-connection inverter is two times higher than that of the three-phase connection inverter E_{dc_Vcon} = $2E_{dc\_threecon}$, it can be concluded that the maximum value of the neutral point potential variation v_{nOUT_MP} of the V-connection inverter is higher than that of the three-phase connection inverter. On the other hand, the CM voltage sources v_{rec} and v_{inv} dominate the magnitude of the CM currents of each system. Therefore, it can be assumed that the magnitude of the CM currents in the V-connection BTB system is higher than that in the three-phase BTB connection system. Moreover, the CM currents dominate the generation of the conducted emission. Based on this, it can also be assumed that the conducted emission of the V-connection BTB system is higher than that of the three-phase connection BTB system.

Table 1 shows the output voltage states of the neutral point potential variation v_{nOUT_MP} of the three-phase connection inverter. From table 1, it can be confirmed that there are seven output voltage states in the three-connection inverter. Table 2 shows the output voltage states of the neutral point potential variation v_{nOUT_MP} of the V-connection inverter. From table 2, it can be confirmed that the number of the output voltages states of the V-connection inverter is less than that of the three-phase connection inverter. Note that in table 1, the DC link voltage of the three phase connection inverter $E_{dc\_threecon}$ = E_{dc}, while in table 2, the DC link voltage of the V-connection inverter E_{dc_Vcon} = $2E_{dc}$.

Fig. 6 shows the distribution of the output voltage state of the neutral point potential variation v_{nOUT_MP} with response to the output voltage vector in both systems. Note that there is an individual mark which is used to represent for each output voltage state. Comparing Fig. 6(a) to Fig. 6(b), it can be confirmed that the number of the switching states of the three-phase connection inverter is more than that of the V-connection inverter. Based on this, it can be concluded that the degree of

Table 1. Ouput voltage states of the neutral point potential variation v_{nOUT_MP} of the three-phase connection inverter. In this case, the DC link voltage $E_{dc\_threecon}$ = E_{dc}

U phase	V phase	W phase	v_{nOUT_MP}
1	1	1	$E_{dc}/2$
1	0	0	$E_{dc}/6$
1	0	1	$E_{dc}/3$
-1	-1	-1	$-E_{dc}/2$
-1	0	-1	$-E_{dc}/3$
-1	0	0	$-E_{dc}/6$
0	0	0	0

Table 2. Ouput voltage states of the neutral point potential variation v_{nOUT_MP} of the V-connection inverter. In this case, the DC link voltage E_{dc_Vcon} = $2E_{dc}$

U phase	V phase	W phase	v_{nOUT_MP}
1	0	1	$2E_{dc}/3$
1	0	0	$E_{dc}/3$
-1	0	-1	$-2E_{dc}/3$
-1	0	1	$-E_{dc}/3$
0	0	0	0

freedom of switching in the three-phase connection inverter is higher than that of the V-connection inverter.

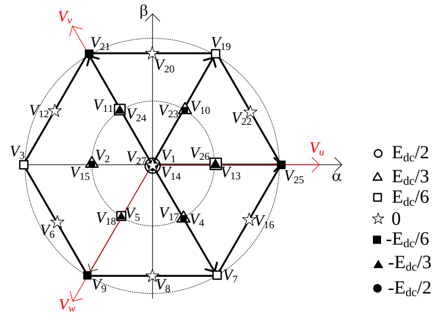
V. Experimental Results

Table 3 shows the experimental conditions. When measuring the conducted emission, a combination between a spectrum analyzer R3131A (Advantest Corporation) and a LISN is applied, and the noise measurement is carried out in a shielded room.

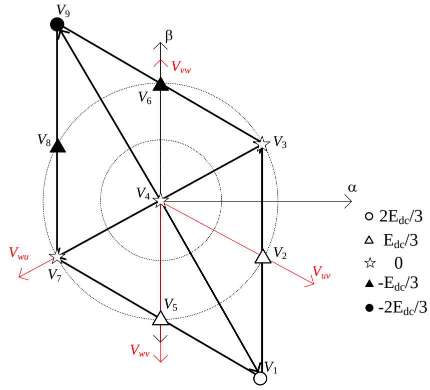
Fig. 7 shows the measurement results of the neutral point potential variation. From Fig. 9, it can be confirmed that the neutral point potential variation of the V-connection BTB system is higher than that of the three-phase connection BTB system.

Fig. 8 shows the harmonic analysis results of the CM leakage currents of both systems. From Fig. 8, it can be confirmed that the CM leakage currents from heat sink, the CM leakage currents of input and output EMC filter of the three-phase connection BTB system is lower than those of the V-connection BTB system. It is because that the neutral point potential variation of the V-connection BTB systems is higher than that of the three-phase connection BTB system. The neutral point potential variation dominates the magnitude of the CM voltage. Hence, the CM voltage source of the V-connection BTB system also becomes higher than that of the three-phase connection BTB system. In addition, the leakage current which flows into LISN i_{CM_LISN} is the smallest among the CM leakage currents. From this, the effect of bypassing the CM leakage current of the input EMC filter is confirmed. Moreover, it can be known that the CM leakage current of the heat sink is dominant in both systems. It is because this CM leakage current is generated from the resonance of the stray capacitance of the IGBT modules C_{GH1}, C_{GH2}, C_{GH3} and the stray inductance of the grounded line of heat sink L_{GH}. From Fig. 5, it can be seen that the CM leakage current of the heat sink has a synthetic CM voltage source v_{rec} + v_{inv}. Therefore, it becomes a dominant CM leakage current.

Fig. 9 shows the measurement result of the conducted emission of both systems. From Fig. 9, in all frequencies from 150 kHz to 30 MHz, it is confirmed that the conducted



(a). Three-phase connection inverter



(b). V-connection inverter

Fig.6. Distribution of the output voltage state of the neutral point potential variation in both systems

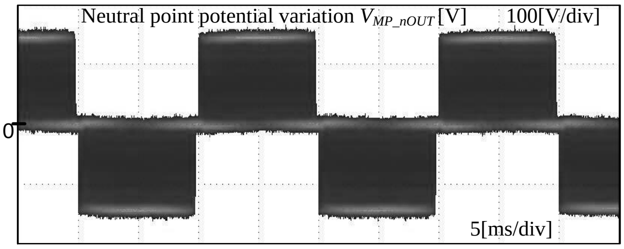
emission of the V-connection BTB system is higher than that of the three-phase connection BTB system. In addition, from Fig. 9(a), in the three-phase connection BTB system, there are the peaks at 550 kHz, 1.6 MHz and 5 MHz. Compared with Fig. 8(a), these peaks of the conducted emission almost matched with the peak's frequencies of the CM leakage current measurement result. Moreover, in the frequencies below 10 MHz, the tendency of the leakage current waveforms, especially the waveform of the leakage current which flows into LISN i_{CM_LISN}, match with the conducted emission measurement result. In the frequencies from 10 MHz to 30 MHz, the conducted emission from gate drive power supplies become considerable [9], [10]. Therefore, in the frequencies from 10 MHz to 30 MHz, the tendency of the conducted emission becomes different from the tendency of the CM leakage currents. From these analyses above, it can be concluded that the CM leakage current dominates the generation of the conducted emission, especially in the frequencies below 10 MHz. In the V-connection BTB system, it can also be confirmed that the CM leakage current dominates the generation of the conducted emission, in similar.

VI. Conclusion

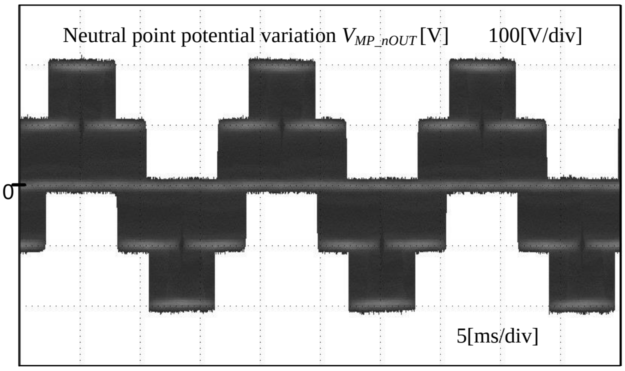
In this paper, the neutral point potential variation of the three-level three-phase connection BTB system and the three-level V-connection BTB system was discussed. As a result, it is confirmed that the neutral point potential variation of the V-connection BTB system is higher than that of the three-phase connection BTB system. It causes the CM leakage currents of the V-connection BTB system become higher. Hence, it can be concluded that since higher neutral point potential variation,

Table 3. Experimental conditions

	V-connection	Three-phase
Input AC Voltage (line -to-line)	200 V	
DC-link voltage	600 V	300 V
Output AC Voltage (line -to-line) & phase current	145 V, 6.4 A	
Output power	1.6 kW	
Power supply frequency	50 Hz	
Output frequency	60 Hz	
Switching frequency	16 kHz	
Load	RL load (13 Ω, 5 mH)	
IGBT module	SK150MLI066T (Semikron)	



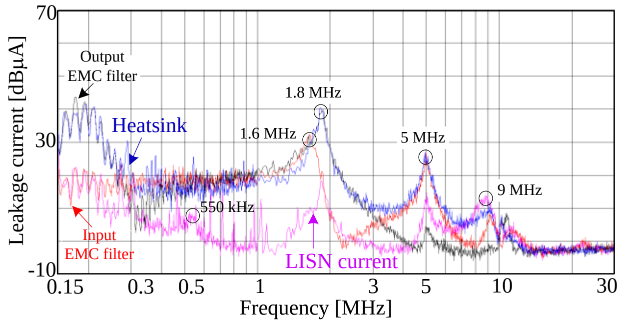
(a). Three-phase connection inverter



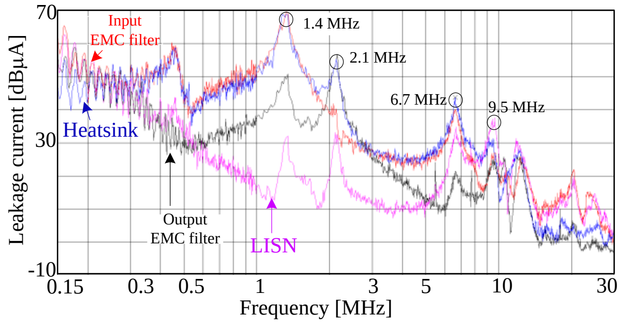
(b). V-connection inverter

Fig.7. Neutral point potential variation, it can be confirmed that the neutral point potential variation of the V-connection BTB system is higher than that of the three-phase connection BTB system

the conducted emission of the V-connection BTB system become higher than that of the three-phase connection BTB system. In the future, in order to reduce the conducted emission of the V-connection BTB system, the switching patterns will be analyzed. Based on this, a new control method which can reduce the conducted emission by suppressing the common-mode voltage in the V-connection BTB system will be derived.



(a) Three-level three-phase-connection BTB system



(b) Three-level V-connection BTB system

Fig.8. Harmonic analysis of CM leakage current

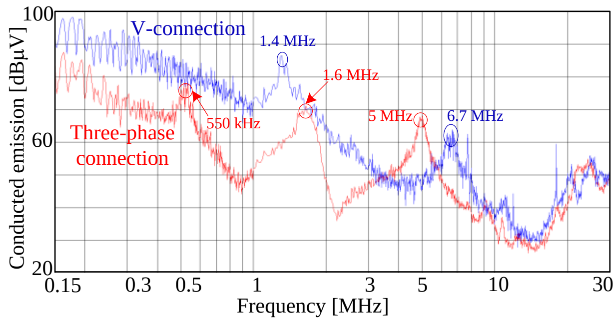


Fig.9. Measurement results of conducted emission in both systems, conducted emission of the V-connection is higher than that of the three-phase connection in all frequencies

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