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Five-Level Common-Emitter Inverter Using Reverse-Blocking IGBTs

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Abstrak

Dalam operasi penyaklaran frekuensi tinggi untuk inverter sumber-arus (CSI), cara konvensional untuk mendapatkan saklar daya satu arah adalah dengan menghubungkan dioda diskrit secara seri dengan saklar daya kecepatan tinggi, seperti power MOSFETs atau IGBTs. Namun, dioda diskrit ini menyebabkan rugi-rugi tambahan pada konverter daya. Makalah ini menyajikan hasil pengujian eksperimen CSI emitor-bersama lima-level dengan penyaklaran frekuensi tinggi menggunakan saklar daya satu arah yang sedang berkembang saat ini, yaitu pemblokingan balik (RB)-IGBTs. Kinerja antara saklar daya satu arah power MOSFETs yang terhubung seri dengan dioda diskrit, dan RB-IGBTs yang tidak menggunakan dioda diskrit juga di uji. Hasil pengujian menunjukkan bahwa dengan menggunakan RB-IGBTs, efisiensi dari konverter daya meningkat jika dibandingkan dengan menggunakan power MOSFET dan dioda diskrit. Namun arus pemulihan balik untuk RB-IGBT ini lebih lambat dibandingkan dioda pemulihan-cepat diskret yang terhubung seri dengan MOSFET daya.

Kata kunci: *common-emitter, CSI, frekuensi tinggi, inverter, multilevel*

Abstract

In a high switching frequency operation of current-source inverter (CSI), a conventional way to obtain unidirectional power switches is by connecting discrete diodes in series with the high speed power switches, i.e. power MOSFETs or IGBTs. However, these discrete diodes will cause extra losses to the power converter. This paper presents experimental test results of high switching frequency five-level common-emitter CSI using the emerging unidirectional power switches, i.e. reverse blocking (RB)-IGBTs. Experimental tests were also conducted to compare the performance between power MOSFETs in series with the discrete diodes, and the RB-IGBTs having inherent reverse blocking capability. The results show that using RB-IGBTs, the efficiency of the power converter increase. However, it is also confirmed that the recently available RB-IGBTs have slow reverse recovery current than the discrete fast-recovery diodes connected in series with power MOSFETs.

Keywords: *common-emitter, CSI, high frequency, inverter, multilevel*

1. Introduction

The ever-lasting development of power semiconductor devices working at high switching frequencies for medium and high power applications such as insulated gate bipolar transistors (IGBTs), and metal-oxide-semiconductor field-effect transistors (MOSFETs) has improved the power converter performance, such as the ability to operate in higher switching speed, low voltage drop, low on-resistance and the ease of their gate drive circuits. Development of high-performance semiconductor switches also increases the research interest in high power converters such as multilevel inverters widely used in industrial application for motor drives, and in new field of smart power grid as renewable energy converters. In industrial sector, numerous industrial applications have begun to require higher power apparatus. Some medium voltage motor drives and utility applications require medium voltage and megawatt power level. For a medium voltage grid, it is troublesome to connect only one power semiconductor switch directly. As a result, a multilevel inverter structure has been introduced as an alternative in high power and medium voltage situations [1], [2]. In general, the multilevel inverter topologies can be classified into two types; voltage-source inverters (VSI) and its dual circuit, i.e., current-source inverters (CSI) [3]. Multilevel inverters have capability to deliver multilevel AC waveform with low-voltage or low-current rating devices, less distorted output

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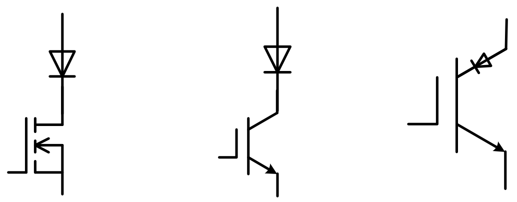
waveforms, lower d*v*/dt or lower d*i*/dt, and resulting in reduction of voltage or current stress in the switching devices, reduction of EMI noise and reduction of the output filter size [4], [5]. The CSI features simple converter topology, motor-friendly waveforms, and reliable short-circuit protection.

Many researchers and engineers have only focused on the multilevel VSI rather than its counterpart, multilevel CSI. Hence, a plenty of multilevel VSI topologies have been presented, but only a few topologies of multilevel CSI can be found in the literatures. As a result, the multilevel VSIs are more widely used than the multilevel CSIs topology. This condition is also caused by some drawbacks in multilevel CSI topologies such as bulky inductors required to obtain smooth DC current sources and the intermediate level currents [6]-[8]. Moreover, even symmetric thyristors having reverse-blocking capability can be used in CSI, however these devices are hard to operate in high switching frequency operation [9]. Thus, in higher switching frequency application, fast recovery discrete diodes are usually connected in series with the power switches, e.g. IGBTs and MOSFETs, to obtain reverse blocking capability. The series diodes often degrade the overall efficiency of the CSIs. However, the series diode will be unnecessary because new IGBTs with reverse-blocking capability (RB-IGBTs) are emerging [10]. Currently, some low and medium power RB-IGBTs are already available in market such as IXRH 50N120 and IXRP 15N120 from IXYS. These RB-IGBTs are very suitable for current-source inverter. It can eliminate the voltage drop caused by the discrete diodes connected in series with the power switches of the conventional unidirectional power switches. This paper presents experimental test results of the new five-level common-emitter CSI operates in high switching frequency operation using RB-IGBTs. The results are also compared to the power MOSFETs in series with fast-recovery blocking diodes.

2. Proposed Five-Level Common-Emitter CSI

2.1. Circuit Configuration and Operation Principle

In the case of VSI, because the power loads are usually have inductive components, power switches with anti-parallel diodes are required to keep current paths of the load. The power switches behave as bidirectional current switches. As dual property of the VSI, in the case of CSI, because filter capacitors are connected in parallel with power load, unidirectional power switches are indispensable in order to prevent short-circuit condition of the filter capacitor. Figure 1 shows various configurations of unidirectional current power switches for high switching frequency application. Figure 1(a) and (b) present unidirectional power switches obtained using power MOSFETs or IGBTs connected in series with discrete diodes. The extra loss caused by the discrete diodes is the main drawback of these power switch configurations. Currently, some power semiconductor companies have been developing unidirectional power switches with inherent reverse blocking capability, i.e. RB-IGBTs as shown in Figure 1(c). This RB-IGBT does not need discrete diode; hence it can reduce the component number, and eliminate the loss caused by the discrete diodes.



(a) (b) (c)

Figure 1. Various configurations of high speed unidirectional power switches: (a) power MOSFET with diode, (b) IGBT with diode, and (c) RB-IGBT

Figure 2 shows a circuit configuration of the three-level common-emitter CSI proposed in [11]-[13], and its principle operation. The inverter is composed by four RB-IGBTs, two diodes, two-DC-current sources, and a filter capacitor C_f connected across the power load. This inverter works generating a three-level output current waveform, i.e. +I, 0 and –I level currents. The main feature of this circuit is that all of the power switches (Q1, Q2, Q3 and Q4) are connected at a common-emitter line. A higher level number of the output current is necessary in order to reduce the d*i*/dt, and to improve the output waveform which also results in the reduction of the output filter size. Figure 3 shows a conventional strategy used to obtain a multilevel output current waveform from the three-level common-emitter inverter. Two three-level common-emitter CSIs are connected in parallel. This topology can generate a five-level output current waveform. By connecting more three-level CSIs in parallel, a higher level of output current waveform can be obtained. If *n* three-level CSIs are connected in parallel, the level number of the output current waveform, *M*, can be calculated as:

$$M=2n+1 \tag{1}$$

However, this topology requires isolated DC current sources for each three-level CSI. Hence, for a higher level output, the number of the isolated DC current sources will be troublesome.

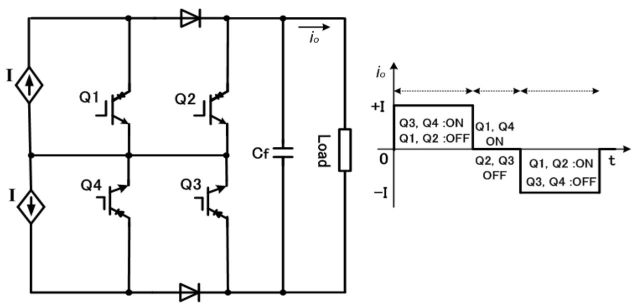


Figure 2. Three-level common-emitter CSI and its output waveform

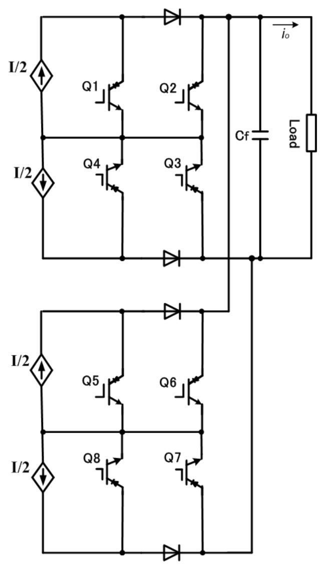


Figure 3. Conventional five-level parallel common-emitter CSI

Figure 4 shows the proposed new configuration of five-level common-emitter CSI. In this figure, all of the DC current sources are assumed to have the identical current amplitude I/2, and the amplitude of the output current is I. A unique point of the proposed five-level CSI circuit is that all of the power switches are connected at a common-emitter or at a common-potential line. Using this circuit topology, the number of the isolated gate drive power supplies can be reduced drastically into a single non-isolated power supply; hence, it can reduce the circuit components and circuit complexity of the gate drive circuits, such as isolation transformers; in case of isolated power supplies are used for each power switch; or capacitors; in case of bootstrap technique is applied. Moreover, all power switches are connected at the identical reference potential; hence it can eliminate the d*v*/dt problem during the switching operation. Therefore, the inverter is more capable to operate at a high switching frequency in order to obtain better quality of the inverter output current by pushing harmonic components to a higher frequency range. Moreover, compare to the five-level parallel common-emitter CSI topology as shown in Figure 3, the proposed five-level CSI does not require isolated DC current sources, and it needs less switch components. The conventional five-level parallel common-emitter CSI needs eight power switches (RB-IGBTs) in total. However the proposed five-level common-emitter CSI needs six RB-IGBTs, only. The current rating of the power switches Q2 and Q3 in the proposed topology is twice compared to the current rating of the power switches in the conventional topology. The voltage ratings are the same for both topologies. The switching state combinations required to generate a five-level current waveform are listed in Table 1. “0” means the switch is OFF, “1” means the switch is ON. Figure 5 shows the operation principle for five-level output current waveform generation, i.e. +I, +I/2, 0, -I/2 and -I current-levels.

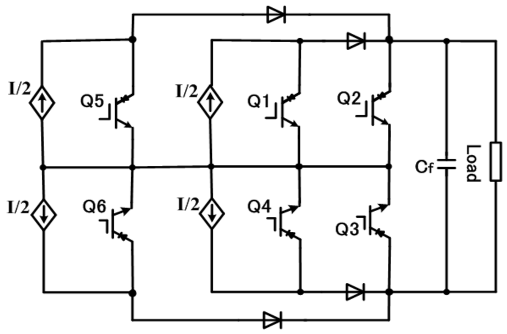


Figure 4. Proposed five-level common-emitter CSI

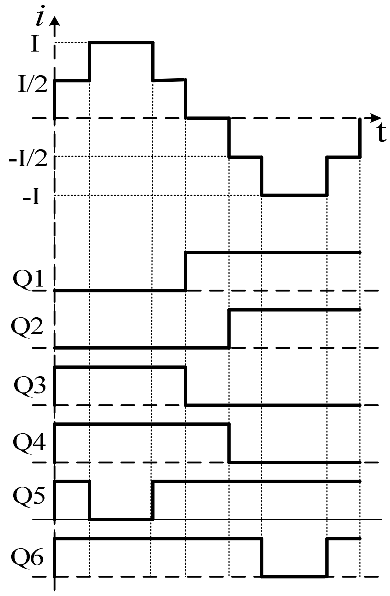


Figure 5. Operation principle of five-level current waveform generation

Table 1. Switching states of proposed five-level CSI

Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Output
0	0	1	1	0	1	+I
0	0	1	1	1	1	+I/2
1	0	0	1	1	1	0
1	1	0	0	1	1	-I/2
1	1	0	0	1	0	-I

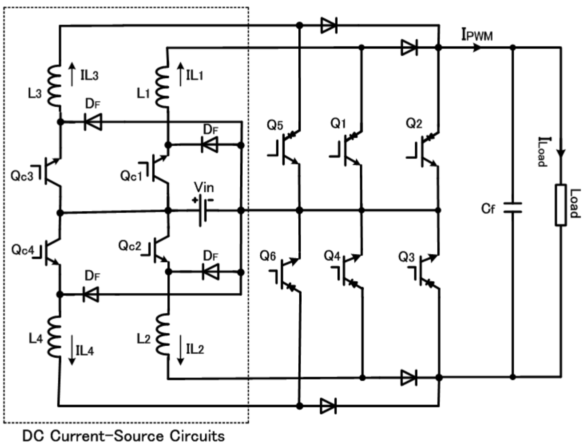


Figure 6. Experimental test circuits of five-level common-emitter CSI

2.2. DC Current Source Circuits and Its Current Control

In the experimental tests of the proposed five-level common-emitter CSI circuits, the DC current sources are obtained by employing chopper circuits with small smoothing inductors working as DC current supply. Figure 6 shows the circuit configurations of the five-level common-emitter CSI including the chopper circuits as DC current sources generator. The chopper circuits consist of four controlled switches, i.e. Q_{C1}, Q_{C2}, Q_{C3} and Q_{C4}, controlling four DC currents flowing through the smoothing inductors L_1, L_2, L_3 and L_4. Four free-wheeling diodes (D_F) are used to keep continuous currents flowing through the inductors.

The current controller of the chopper circuits for DC current generation is presented in Figure 7. Proportional integral (PI) regulators are independently applied to control the currents flowing through the smoothing inductors, which determine the amplitude of the PWM output current waveform (I_{PWM}) simultaneously. Making the inductor currents (I_{L1}, I_{L2}, I_{L3} and I_{L4}) follow the reference current (I_{ref}) is the objective of this current regulator. The gating signals of the chopper switches are generated by comparing the error signals of the detected steady state currents flowing through the smoothing inductors, and a triangular waveform after passing through the PI regulator. This signal is used to control the duty cycles of the chopper switches to obtain balanced and stable DC currents I_{L1}, I_{L2}, I_{L3}, and I_{L4}.

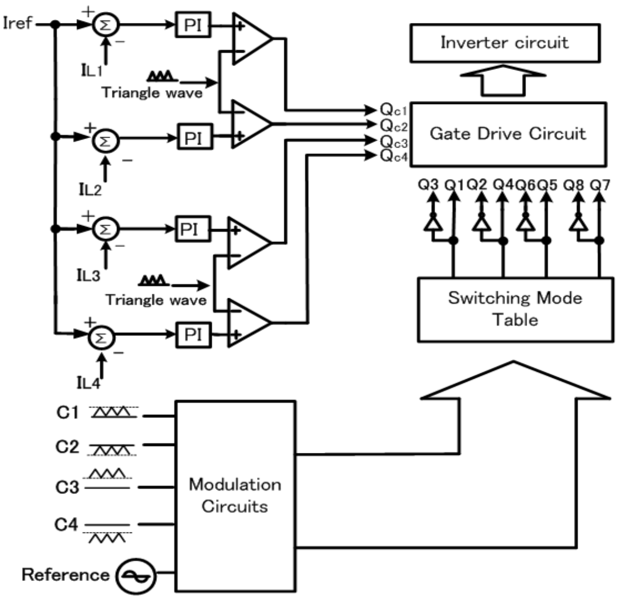


Figure 7. Current control diagram

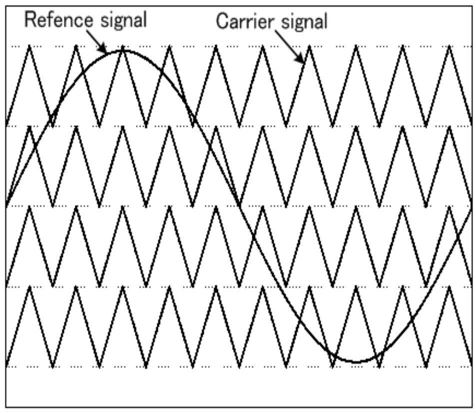


Figure 8. Multi-carrier based sinusoidal PWM

2.3. PWM Modulation Strategy

In order to obtain a better output current waveform, a pulse width modulation (PWM) technique is applied, instead of a staircase waveform operation. Staircase waveform can easily be obtained at the fundamental switching frequency, so switching losses can be negligibly low. However more distortion of the output waveform is generated and a larger filter is needed. In this paper, a level-shifted multi-carrier based sinusoidal PWM technique is employed to generate the gate signals for the CSI power switches to obtain the PWM current waveforms as shown in Figure 7, and Figure 8 in more detail. All carrier waveforms (C_1, C_2, C_3 and C_4) are in phase with the identical frequency. The frequency of the reference sinusoidal waveform determines the fundamental frequency of the output current waveform, while the frequency of triangular carrier waves gives the switching frequency of the power switches. An *M*-level output current waveform using this modulation requires (M-1) triangular carriers with the same frequency [13]-[15].

3. Research Method

In order to verify and to test the performance of the proposed five-level common-emitter CSI configuration experimentally, laboratory prototype of the five-level common-emitter CSI was constructed using IXRP15N RB-IGBTs manufactured by IXYS. In order to compare the switching characteristics of the RB-IGBTs, power MOSFETs (FK30SM-6) in series with fast recovery diodes (HFA16PB120) were also used as power switches of the inverter. The experimental circuit specifications are listed in Table 2. The control circuits of choppers and inverter were built using mixed analog and digital circuits with opto-coupler as isolations between control circuits and power converter.

Table 2. Test parameters

Parameter	Value
Smoothing inductors of chopper	1 mH
Power source voltage	DC 160 V
Switching frequency	22 kHz
Filter capacitor (Cf)	5 F
Load	R= 6 Ω , L= 1.2 mH
Output current frequency	50 Hz

4. Results and Discussion

Figure 9 shows the experimental waveforms of the five-level CSI showing the load current, five-level PWM output current, and one of the DC current source waveforms obtained using 1 mH smoothing inductors. The total harmonic distortion (THD) of the five-level PWM current is 4.19% calculated up to 40th harmonic components. As can be seen in the figure, low distorted sinusoidal load current waveform was obtained after filtering by a small 5-μF filter capacitor. Figure 10 shows the conduction loss characteristics of the five-level CSI using the RB-IGBTs, and power MOSFETs in series with fast-recovery diodes. As can be seen in the figure, the RB-IGBTs generate smaller loss for higher output power of five-level CSI.

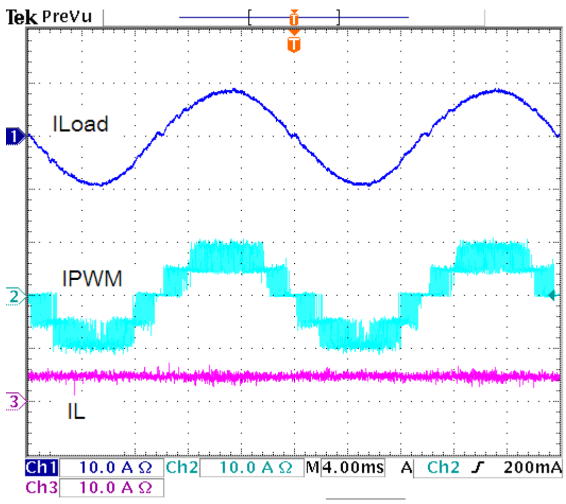


Figure 9. Load current (I_{Load}), five-level current (I_{PWM}) and smoothing inductor current waveforms (I_L); (scales: amplitude 10 A/div, time 0.4 ms/div)

Moreover, Figure 11 shows the efficiency characteristics of the proposed five-level common-emitter CSI built using RB-IGBTs, and power MOSFETs with discrete diodes. The efficiency is low in a light load condition which is caused by the conduction losses of the inductors and switching devices becoming relatively dominant against the load power. However, the efficiency increases as the load becomes heavier, and the maximum efficiency of the five-level CSI built using RB-IGBTs was confirmed to be 89.5 %. The figure shows that the efficiency of the proposed five-level common-emitter CSI using the RB-IGBT is higher than using power MOSFETs with discrete diodes. Figure 12 shows the enlarged figures of the PWM output current waveform generated by CSI built using RB-IGBTs, and power MOSFETs with discrete diodes. This figure shows that the RB-IGBT has slower reverse recovery current than the fast-recovery discrete diode connected in series with power MOSFET.

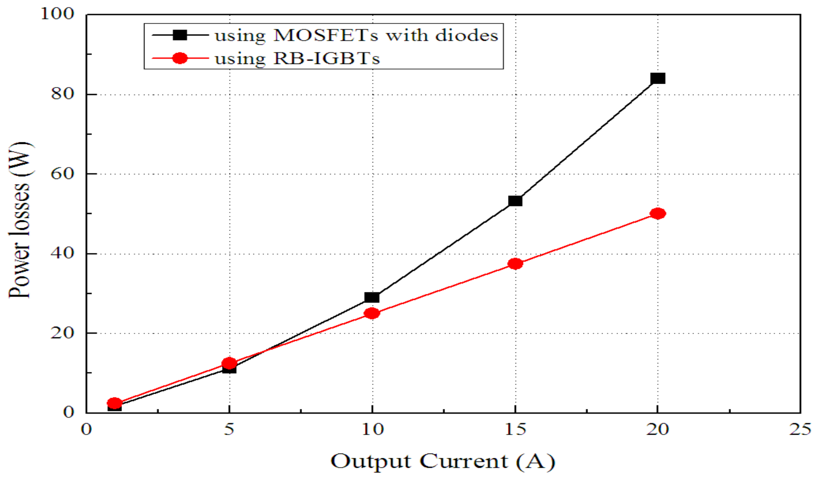


Figure 10. Conduction loss characteristics

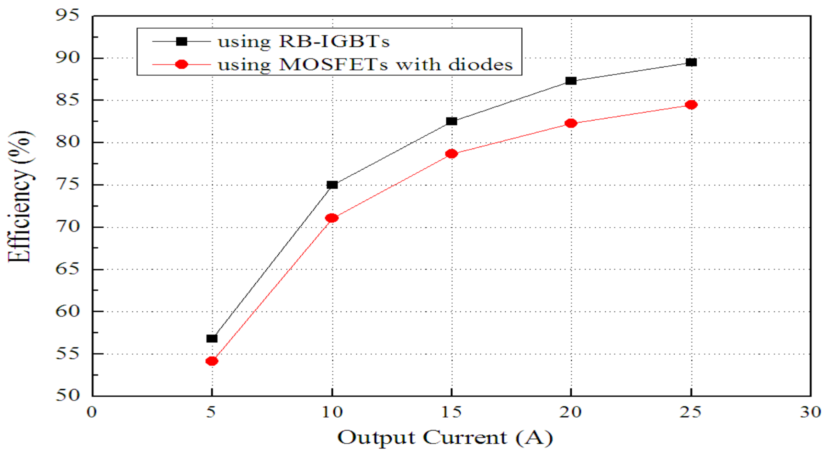


Figure 11. Efficiency comparison for each kind of power switches

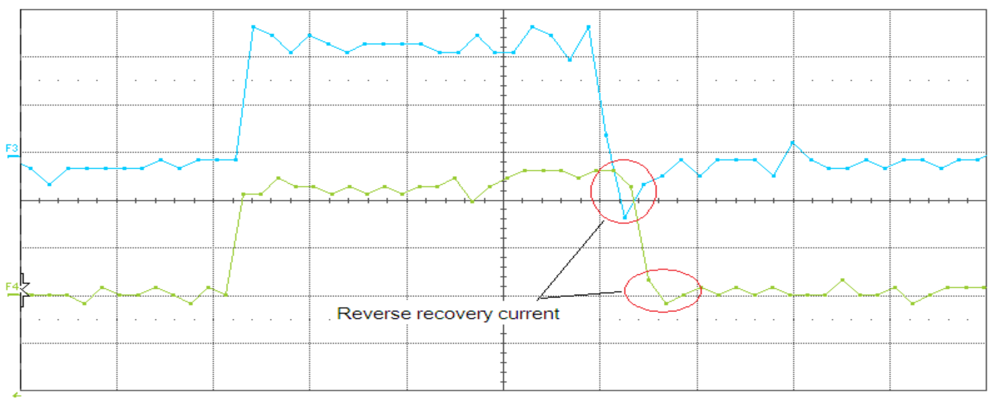


Figure 12. The enlarged figures of PWM output current: using reverse-blocking IGBTs (upper graph), and using power MOSFETs in series with discrete diodes (lower graph); (scales: amplitude 500 mA/div, time 5.5 μs/div)

5. Conclusion

This paper presented experimental test results of the new five-level common-emitter CSI built using RB-IGBTs. The performance characteristics of the RB-IGBTs and power MOSFETs with series discrete diodes were also investigated. The results show that using RB-IGBTs, the efficiency of the power converter will increase. It is caused by the elimination of the losses caused by the discrete diodes connected in series with the power MOSFETs. However, it is also confirmed that the recently available RB-IGBTs have slow reverse recovery current than the discrete fast-recovery diodes connected in series with power MOSFETs.

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