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A zero-current-switching based three-phase PWM inverter having resonant circuits on AC-side

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A Zero-Current-Switching Based Three-Phase PWM Inverter Having Resonant Circuits on AC-Side

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Abstract — **This paper presents a zero current switching based three-phase PWM inverter having small resonant circuits on the ac side, the resonant frequency of which is 50kHz. The zero current switching inverter can greatly reduce the switching losses and electromagnetic noises. In this paper, the principle of zero current switching operation, the design of the resonant circuits and the control sequence are described from a theoretical and practical point of view. Moreover, experimental results obtained from a zero current switching PWM inverter which is driving an induction motor of 2.2kW are shown to verify the practicability.**

I. INTRODUCTION

With remarkable progress of switching devices such as IGBT's and power MOSFET's, the switching frequency of voltage source PWM inverters has been higher and higher. High frequency switching of a PWM inverter gives great benefits in reduction of harmonic voltage and current ripples. In particular, acoustic noises can be eliminated by setting the switching frequency over 20kHz. Such a high frequency PWM inverter which is based on hard switching technique, however, may cause increase of switching losses and electromagnetic noises.

On the other hand, soft switching technique has been researched and developed for power converters [1, 2, 3, 4]. It realizes zero voltage and/or current switching with the help of resonant circuits. Soft switching inverters are characterized by a great reduction of switching losses and noises. Divan has proposed resonant dc link inverters [1, 2] for ac motor drives which are based on zero voltage switching.

This paper presents a zero current switching (ZCS) based three-phase PWM inverter for ac motor drives. It has small resonant circuits on the ac side of the inverter. The current flowing in a switching device is a sum of the load current and the resonant current. The switching device is controlled to be always turned on and off at zero current by regulating the amplitude of the resonant current larger than the load current. The amplitude of the resonant current in one phase can be controlled independently of other phases because the neutral point of the resonant circuits is connected to that of the dc link.

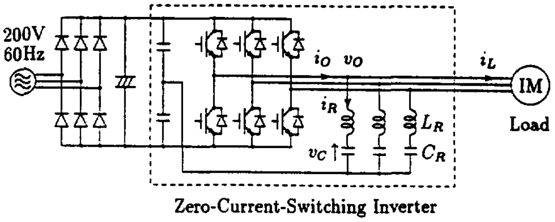

Fig.1. System Configuration of Zero Current Switching Based Three-Phase PWM Inverter.

This paper describes the principle of the zero current switching operation, the design of the resonant circuits, and the control scheme for the new soft switching inverter, along with some interesting experimental results obtained by a prototype system of 4kVA.

II. SYSTEM CONFIGURATION

Fig.1 shows a circuit configuration of the zero current switching (ZCS) based PWM inverter. The ZCS inverter consists of a conventional three-phase voltage-source inverter using six IGBT's and three series resonant circuits which are wye-connected and installed on the ac side of the inverter. The neutral point of the wye-connected resonant circuits is connected to that of the dc link, the voltage of which is sustained by two capacitors. In the following experiments, an induction motor of 2.2kW is used as a load.

The current flowing through a switching device is a sum of the load current and the resonant current. If the amplitude of the resonant current is larger than the load current, zero-crossing of the current in the switching device appears. This allows the switching device to be turned on or off at the time of the zero-crossing. The connection of the neutral point between the resonant circuits and dc link makes it possible to control the resonant current in each phase independently.

The maximum frequency of the zero current switching based inverter is half as high as the resonant frequency, because a switching device can be turned on or off once a resonant cycle. In the following experiments, IGBT's are used as switching devices, so that the resonant frequency

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f_R is designed to be 50kHz.

$$f_R = \frac{1}{2\pi\sqrt{L_R C_R}} = 50\text{kHz}$$

On the other hand, the amplitude of the resonant current should be larger than that of the load current in order to achieve the zero current switching operation. Let's discuss a design for the three-phase inverter rating of 200V, 4kVA, and the dc link voltage of 280V. The inverter has a current rating of 16A, so that the amplitude of the resonant current has to be set to 20A. The applied voltage across a resonant circuit is 140V, that is, a half of the dc link voltage. Therefore, the characteristic impedance should be set as

$$Z_R = \sqrt{\frac{L_R}{C_R}} = 7\Omega.$$

From these requirements, the circuit constants in the ZCS inverter developed here are set as $L_R = 20\mu$H and $C_R = 0.5\mu$F.

III. ZERO CURRENT SWITCHING OPERATION

A. *Switching Modes and Resonant Current*

Fig.2 shows a single phase equivalent circuit and five switching modes. Zero current switching operation can be discussed by using the single phase equivalent circuit, because the independent control of the resonant current in each phase is achieved.

Tr_1 is conducting in mode I as shown in Fig.2(b), while D_1 is conducting in mode II as shown in Fig.2(c). These two modes are different in the direction of the output current i_O. The voltage across the resonant circuit, or the output voltage of the inverter, v_O is equal to $+E/2$ in modes I and II. Figs.2(d) and (e) show modes III and IV. In modes III and IV, v_O is equal to $-E/2$. Fig.2(f) shows mode V, in which neither IGBT nor diode is conducting, so that the load current i_L is flowing through the resonant circuit and charging or discharging the resonant capacitor.

Assuming that no resistor is included in the resonant circuit, the following equations are obtained from the equivalent circuit.

$$v_O = L_R \frac{di_R}{dt} + v_C \tag{1}$$

$$v_C = \frac{1}{C_R} \int i_R dt \tag{2}$$

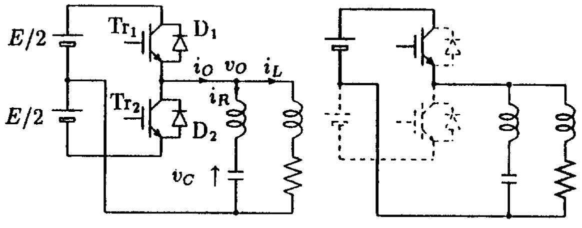
Assuming that v_O is a constant voltage for modes I, II, III and IV, the resonant current i_R is given by

$$\begin{aligned} i_R(t) &= \sqrt{\frac{C_R}{L_R}} \{v_O - v_C(0)\} \sin \omega t \\ &+ i_R(0) \cos \omega t, \end{aligned} \tag{3}$$

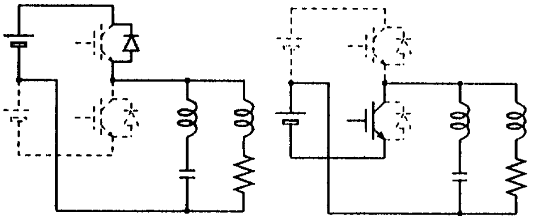
and the resonant capacitor voltage v_C is given by

$$\begin{aligned} v_C(t) &= v_O + \{v_C(0) - v_O\} \cos \omega t \\ &+ \sqrt{\frac{L_R}{C_R}} i_R(0) \sin \omega t, \end{aligned} \tag{4}$$

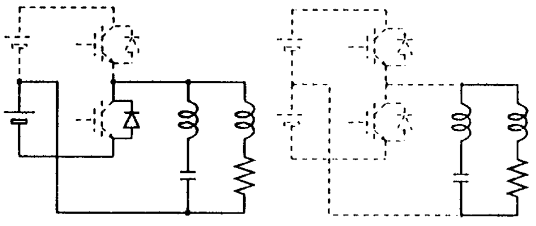
where $i_R(0)$ and $v_C(0)$ are initial values of i_R and v_C at the time of $t = 0$, and $\omega = 1/\sqrt{L_R C_R}$.



(a) Equivalent Circuit. (b) Mode I.



(c) Mode II. (d) Mode III.



(e) Mode IV. (f) Mode V.

Fig.2. Switching Modes in ZCS operation.

Assuming that i_R is equal to $-i_L$ in mode V, the voltage across the resonant circuit, or the inverter output voltage, v_O is obtained by

$$v_O = -L\frac{di_L}{dt} - \frac{1}{C_R}\int i_L dt. \tag{5}$$

B. *Switching Sequence*

Fig.3 shows a principle of the zero current switching operation. Assume that the load current i_L is kept a constant current I_L during a few resonant cycles, and that no resistor exists in the resonant circuit. At the time of $t = 0$ in Fig.3, the initial values of v_C and i_O are equal to zero, that is, $i_R(0) = -i_L(0)$.

At the time of $t = 0$, Tr_1 is turned on, so switching mode becomes mode I. After the time of $t = 0$, the current

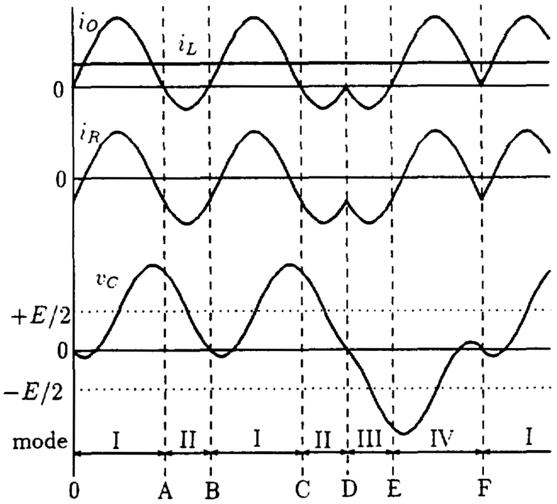


Fig.3. Principle of Zero Current Switching Operation.

in the switching device, i_O is rising up because the step voltage of $+E/2$ is applied across the resonant circuit. From Eq.4, i_R and v_C are given as follows:

$$i_R(t) = \sqrt{\frac{C_R}{L_R}}\frac{1}{2}E\sin\omega t - I_L\cos\omega t \tag{6}$$

$$v_C(t) = \frac{1}{2}E(1-\cos\omega t) - \sqrt{\frac{L_R}{C_R}}I_L\sin\omega t. \tag{7}$$

The peak value of the resonant current, I_R is equal to

$$I_R = \sqrt{\frac{C_R}{L_R}\left(\frac{1}{2}E\right)^2 + {I_L}^2}.$$

The current in the switching device, i_O is a sinusoidal waveform biased by I_L, and i_O reaches zero current at the time of t =A. Switching mode changes into mode II at the time because of $i_O < 0$, so that the resonant current continues to flow until the time of t =B. At the time, i_R and v_C are equal to their initial values respectively because the time interval of one resonant cycle of $T = 2\pi\sqrt{L_R C_R}$ passed from the time of t =0. If Tr$_1$ is continuously provided the gate signal, switching mode will be changed into mode I again at the time of t =B.

Let's discuss how to change switching mode from mode I to mode III. At the times of t =C and D, i_O reaches zero current. If switching mode were changed to mode III at the time of t =C, the peak value of the resonant current, I_R is

$$I_R = \sqrt{\frac{C_R}{L_R}\left(\frac{3}{2}E\right)^2 + {I_L}^2},$$

because the initial value of v_C is equal to E and the initial value of i_R is equal to $-I_L$. Therefore, switching mode can be changed to mode III at the time t =D. Then the initial value of v_C is equal to zero and the initial value of i_R is equal to $-I_L$, so that the peak value of i_R in the time interval between t =D and $t = F$ is

$$I_R = \sqrt{\frac{C_R}{L_R}\left(\frac{1}{2}E\right)^2 + {I_L}^2},$$

which is the same as that before the time of t =D. The gate signal is removed from Tr$_1$ at the time of t =C and is given to Tr$_2$ at the time of t =D, because a blanking time is required to avoid the short-circuit between Tr$_1$ and Tr$_2$. As a result, switching mode is changed from mode III to mode I at the time of t =F.

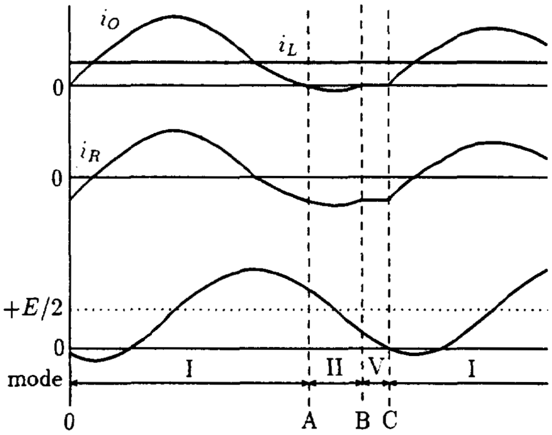


Fig.4. Control of Amplitude of Resonant Current.

C. Resonant Current Control

Fig.4 illustrates the switching sequence for controlling the amplitude of the resonant current. The resonant current is damped down by a resistor present in the resonant circuit and equivalent one in the switching devices, so that i_O would not reach zero current. In such a case, the amplitude of the resonant current can be increased by the selection of mode V in Fig.4.

At the time of t =B, the current in the switching device, i_O is zero, but the voltage across the resonant capacitor, v_C does not reach zero because the resonant current is damped by the resistor. Two IGBT's of Tr$_1$ and Tr$_2$ are turned off, and the switching mode is changed to mode V if the voltage across the resonant circuit, v_O is lower than $E/2$. Since it is assumed that the load current is constant, Eq.5 tells us that v_O is nearly equal to v_C. If the amplitude of the resonant current i_R became zero due to damping, the voltage across the resonant capacitor, v_C

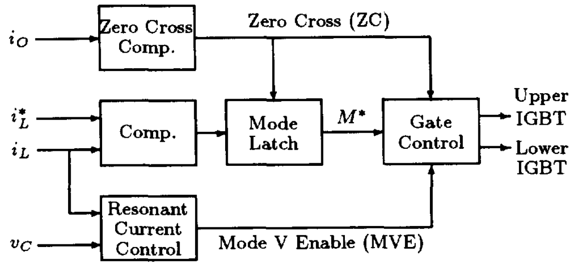


Fig.5. Control Circuit for Zero Current Switching Inverter.

would be equal to $E/2$. If no damping is assumed, v_C reaches zero at the time of t =B.

Since the load current i_L flows through the resonant circuit, it discharges the resonant capacitor as

$$v_C = -\frac{1}{C_R}\int i_L dt. \tag{8}$$

At the time of t =C, v_C reaches zero, so that switching mode is changed to mode I again. The amplitude of the resonant current increases because the voltage across the resonant reactor at the time of t =C is equal to that at the time of t =0, which is equal to $E/2$.

IV. CONTROL CIRCUIT

Fig.5 shows the control circuit in one phase for the zero current switching based PWM inverter. The PWM inverter developed in this paper controls the load current i_L to follow its reference $i_L{}^*$. To determine which should be turned on Tr_1 or Tr_2 in Fig.2, i_L is detected and compared with $i_L{}^*$. The mode latch in Fig.5 holds the next switching mode request M^* to avoid the change of the mode request during commutation. The comparator has no hysteresis width because the inverter can be turned on or off only once a resonant cycle without any limitation for the switching frequency as mentioned above.

The resonant current control circuit regulates the amplitude of the resonant current by introducing mode V. Table I shows the requirement for the selection of mode V. In the case of $i_L < 0$ and $v_C < 0$, or in the case of $i_L > 0$ and $v_C > 0$, the resonant capacitor voltage v_C can approach to zero by the selection of mode V. However, the selection of mode V can not force v_C to be zero in the case of $I_L < 0$ and $v_C > 0$, or in the case of $I_L > 0$ and $v_C < 0$. In the case that i_L is equal to zero, no discharge occurs in v_C during the selection of mode V. The load current is classified into three states by comparison with $-I_{th}$ and I_{th}. Inputing the three states of the load current and the polarity of v_C, the resonant current control circuit outputs a mode V enable signal according to Table I. The photo-coupler is used to isolate the polarity signal of v_C.

TABLE I
REQUIREMENT FOR CONTROLLING RESONANT CURRENT.

	$i_L < -I_{th}$	$-I_{th} < i_L < I_{th}$	$I_{th} < i_L$
$v_C > 0$	next mode	next mode	mode V
$v_C < 0$	mode V	next mode	next mode

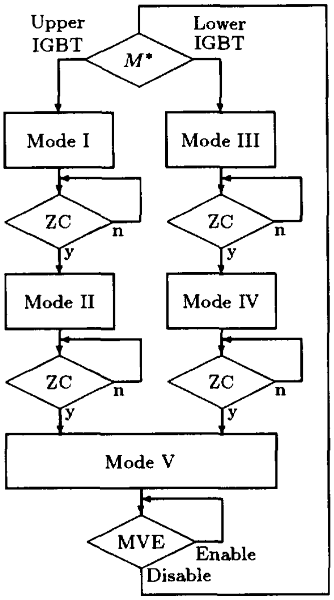


Fig.6. Control Sequence of Gate Signal.

Fig.6 shows the control sequence of the gate control circuit in Fig.5. It outputs mode I or mode III by the mode request M^*, in which the corresponding IGBT is conducting. The first zero cross signal of i_O changes the switching mode to mode II or mode IV, in which the corresponding free wheeling diode is conducting. The second zero cross signal changes the switching mode to mode V, which is kept until mode V enable signal is disable.

V. EXPERIMENTAL RESULTS

Figs.7 to 9 show the experimental waveforms of the ZCS PWM inverter connected to a three-phase L–R load of L = 13mH and $R = 7\Omega$. In these experiments, the dc link voltage of the inverter is set to be 200V.

Fig.7 shows the load current i_L, the inverter output current i_O, and the inverter output voltage v_O. The load current i_L has a sinusoidal waveform, and i_O is a sum of i_L and the resonant current i_R. Since the amplitude of i_R is controlled to be constant, the inverter can be turned on and off at zero current. The output voltage of the inverter

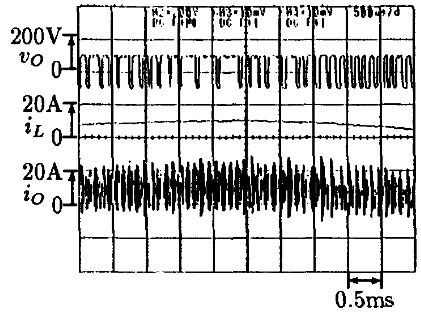


Fig.7. Experimental Waveforms of v_O, i_L and i_O.

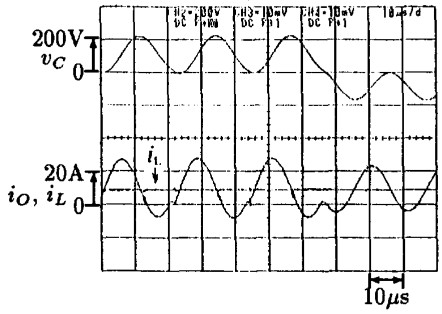


Fig.8. Experimental Waveforms in Case of Change from Mode I to Mode III.

is shaped into a PWM waveform. The minimum pulse width is 20μs because the inverter can be turned on or off once a resonant cycle of 20μs. Here, the average switching frequency is about 5kHz, while the resonant frequency is 50kHz.

Fig.8 shows the close-up waveforms in commutation from mode I to mode III. The mode change is achieved at zero current. The resonant current after the commutation has the same amplitude as that before the commutation because the capacitor voltage is nearly equal to zero at the commutation. Fig.9 shows interesting experimental waveforms in the case of controlling the amplitude of the resonant current by the selection of mode V. Note that i_O is equal to zero during mode V. Then the load current continues to flow through the resonant circuit and to discharge the resonant capacitor until reaching zero voltage. Therefore, the amplitude of the resonant current can be kept constant.

Fig.10 shows experimental waveforms in which the ZCS inverter is driving an induction motor of 2.2kW. Here the output frequency of the inverter is about 40Hz, and the output power of the induction motor is about 1.5kW.

Fig.11 shows experimental waveforms of the collector to emitter voltage v_{CE} and the collector current i_C of an upper IGBT being turned on. Fig.12 shows those of the IGBT being turned off. These two figures are obtained from the proposed soft switching based inverter. Figs.13 and 14 show those obtained from a hard switching based inverter, which is a conventional PWM inverter. Those are measured under the same conditions that the dc link voltage is equal to 260V and the load current i_L is equal to 12A. In Fig.13, a spike current appears in i_C, which has a peak value of 10A, at the IGBT being turned on, because the lower free wheeling diode is conducting before the IGBT is turned on. In Fig.14, a surge voltage of v_{CE} occurs. Almost all of the switching losses in the hard switching based inverter is produced at the turn-off of the IGBT, because the fall time of i_C is about 1μs. On the other hand, the soft switching based inverter has neither spike current nor surge voltage. Since the collector current i_C is nearly equal to zero at the turn-on and off of the IGBT, the soft switching based inverter can greatly reduce the switching losses, compared with the hard switching based inverter.

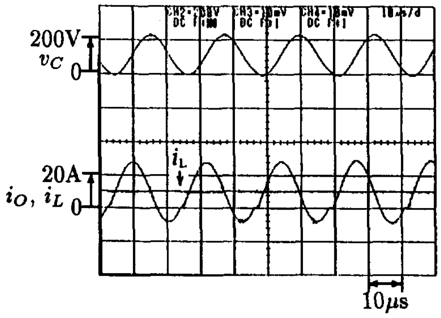


Fig.9. Experimental Waveforms in Case of Controlling Amplitude of Resonant Current.

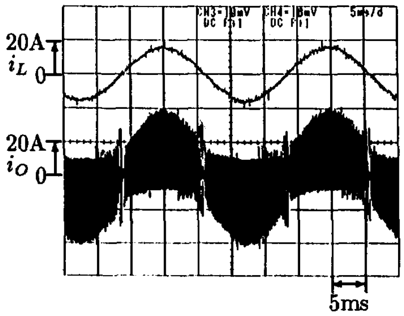


Fig.10. Experimental Waveforms in Case of driving Induction Motor.

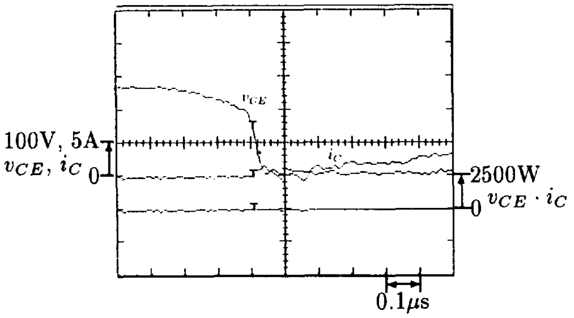


Fig.11. Experimental Waveforms at Turn on in Zero Current Switching.

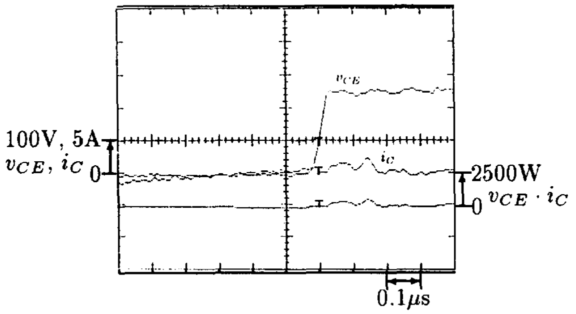


Fig.12. Experimental Waveforms at Turn off in Zero Current Switching.

VI. Conclusion

In this paper, a zero current switching based three-phase PWM inverter is proposed, which has small resonant circuits on the ac side. The proposed inverter is characterized by the followings.

- The soft switching based PWM inverter can greatly reduce the switching losses, compared with a conventional hard switching inverter.
- The resonant current is independently controlled in each phase because the neutral point of the wye-connected resonant circuits is connected to that of the dc link.
- The soft switching based PWM inverter can drive ac motors without any restriction as if it were a conventional three-phase voltage source PWM inverter.

The zero current switching based three-phase PWM inverter of 4kVA, which was developed in this paper, gives some interesting experimental results, showing the possibility of its practical use.

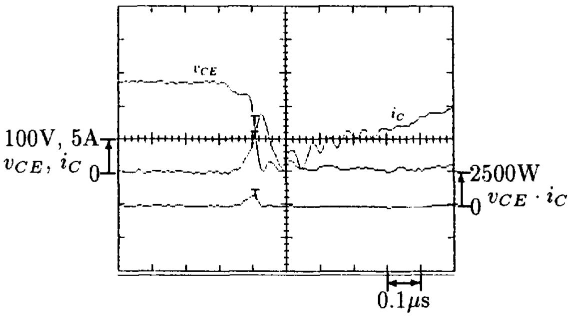


Fig.13. Experimental Waveforms at Turn on in Hard Switching.

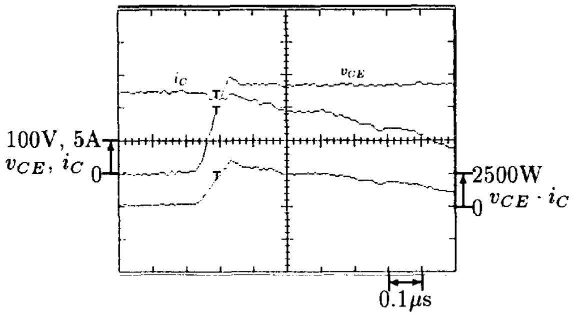


Fig.14. Experimental Waveforms at Turn off in Hard Switching.

References

[1] D. M. Divan: "The Resonant DC Link Converter – A New Concept in Static Conversion," IEEE/IAS Annual Meeting, pp.648 (1986)

[2] D. M. Divan, and G. Skibinski: "Zero-Switching-Loss Inverters for High-Power Applications," IEEE Trans. Ind. Appl., Vol.25, No.4, pp.634 (1989)

[3] J. A. Ferreira, P. C. Theron, and J. D. van Wyk: "Control of Nonlinear Resonant Pole Inverters," IEEE/IAS Annual Meeting, pp.834 (1991)

[4] H. Yonemori, and M. Nakaoka: "Advanced Soft-Switching Sinewave PWM High-Frequency Inverter – Link Cycloconverter Incorporating Voltage-clamped Quasi-Resonant and Capacitive Snubber Techniques," IEEE/IAS, Annual Meeting, pp.795 (1991)