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A New Hybrid Control Scheme Using Active-Clamped Class-E Inverter with Induction Heating Jar for High Power Applications

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ABSTRACT

This paper presents a new hybrid control scheme using Active-Clamped Class-E (ACCE) inverter for the Induction Heating (IH) jar. The proposed hybrid control scheme has characteristics, which acts as class-E inverter at lower switch voltage and ACCE inverter at higher switch voltage than reference voltage of the main switch by feeding back voltage of the switch. The proposed hybrid control scheme also has advantages of conventional ACCE inverter such as Zero-Voltage-Switching (ZVS) of the main switch and the reduced switch voltage due to clamping circuit. Moreover, the proposed hybrid control method using ACCE inverter has higher output power than conventional control scheme since ACCE inverter operates like class-E inverter at low input voltage condition. The principles of the proposed control are explained in detail and the validity of the proposed control scheme is verified through the several interesting simulated and experimental results.

Key Words: Hybrid control scheme, Class-E inverter, Active-Clamped Class-E inverter (ACCE), Induction Heating (IH), Zero-Voltage-Switching (ZVS)

1. Introduction

With the remarkable progress of the power semiconductor devices and control scheme, much attention has been focused on the research and developments of high frequency resonant inverters for supplying high power to IH (induction heating) load. Also, IH has many advantages including cleanness, safety, high efficiency, maintainability and controllability. The various resonant inverters, which are Class-D, Class-E and ACCE (Active-Clamped Class-E) inverter using power devices such as MOSFETs and IGBTs offer reduced switching loss by effective means of soft-switching technique and attractive possibilities in developing higher frequency of operation, higher efficiency, small size and light weight [1]-[9]. Among them, Class-E inverter is widely used as a main topology for IH jar. Fig. 1 shows the overall system of the Class-E inverter for IH jar. Req and Leq are equivalent resistor and inductor of working coil respectively.

The Class-E inverter system has more advantages than other inverter systems since it needs only one power semiconductor device. It means that Class-E inverter system embodies low cost system and also it accomplishes zero-voltage-switching (ZVS) by resonant at turn-on. However, it has some drawbacks such as increased conduction loss and reduced switch utilization.

To solve these problems ACCE inverter has been studied recently. ACCE inverter has been widely applied to the DC-Link resonant inverter by reducing the voltage stress due to the clamping of the main switch voltage when it is compared with the Class-E inverter[3-6].

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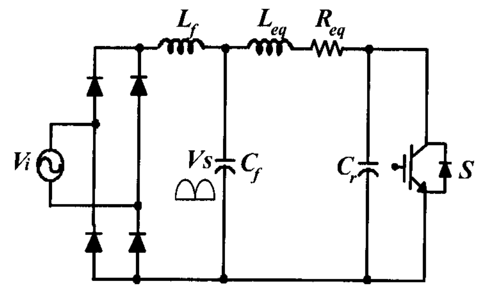


Fig. 1. Class-E inverter system for IH Jar application.

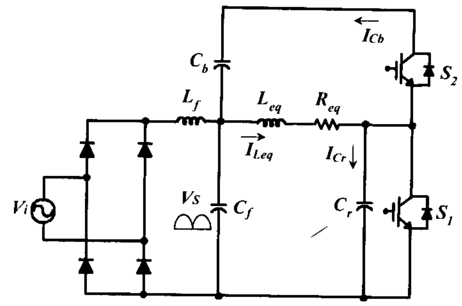


Fig. 2. Active-Clamped Class-E (ACCE) inverter system for IH Jar application.

By these advantages, this paper uses ACCE inverter as a main circuit for IH jar applications. In case of the IH jar applications, output power of the ACCE inverter is reduced in comparison with the Class-E inverter because the overall resonant energy is decreased with the reduced clamp voltage of the switch in case of using the same parameters and control of the system. Therefore, ACCE inverter should require higher current stress of the main switch than the Class-E inverter to obtain an identical output power under the same conditions. As a result, it increases the conduction loss of the switch and decreases the system efficiency. Also, it has serious problems that increased current requires the high rated current of the switch and decreases utilization of the switch.

Therefore, a new hybrid control scheme of ACCE inverter for high power applications is presented in this paper. The proposed hybrid control scheme makes ACCE inverter operate in ACCE inverter mode or Class-E inverter mode to increase output power and clamp the switch voltage. Therefore, the problems mentioned above are reduced. The principles of the proposed control scheme are explained in detail and the validity of the proposed control scheme is verified through the several interesting simulated and experimental results.

2. Operation Principle of the ACCE Inverter

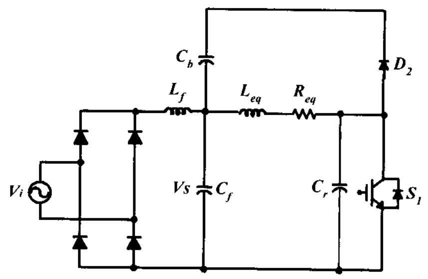
2.1 Circuit description

Fig. 2 shows the overall ACCE inverter system for IH jar with a small input filter (L_f & C_f). It consists of conventional class-E inverter including the main switch, S_1, the resonant capacitor, C_r, the equivalent resistor, R_{eq}, and the equivalent inductor, L_{eq}, of IH jar and the auxiliary circuit, which has the auxiliary switch, S_2, and the clamp capacitor, C_b.

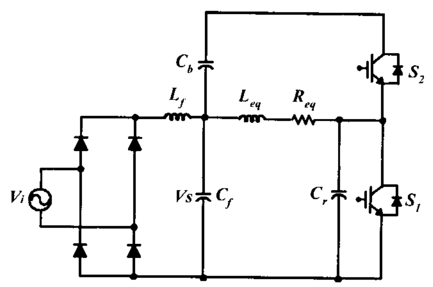
2.2 ACCE inverter system with the proposed hybrid control scheme

Fig. 3 shows two operation modes of the ACCE inverter system with the proposed control scheme, which senses the main switch voltage increased due to the input voltage V_S.

As shown in Fig. 3 (a), the proposed ACCE inverter system operates like the conventional class-E inverter when the voltage of main switch, S_1, is below the clamp voltage.



(a) Class-E inverter mode below the clamp voltage of the switch S_1



(b) ACCE inverter mode above the clamp voltage of the switch S_1

Fig. 3. The divided two operation modes of the ACCE inverter system with the proposed hybrid control scheme.

On the other hand, it operates like the conventional ACCE inverter system due to the operating of the auxiliary circuit when the voltage of main switch, S_1, is above the clamp voltage as shown in Fig. 3 (b). To analyze operating modes of the ACCE inverter system with the proposed control scheme, we make the following assumptions.

- All components are ideal.
- Input voltage of DC link is constant in one switching cycle.
- Inverter operates in steady state.

From the analysis of reference [7], Class-E inverter mode of the ACCE inverter system with the proposed control scheme is omitted and ACCE inverter mode is only considered and analyzed in detail in case of the IH jar in this paper. Fig. 4 shows theoretical waveforms and Fig. 5 shows eight operating modes of the ACCE inverter.

(a) Turn-on state of the main switch (Mode 1, 2, 3)

The main switch turns on under ZVS condition and the load current, i_{Leq} flows through $L_{eq} \rightarrow R_{eq} \rightarrow S_1 \rightarrow V_s$. Voltage equation of the equivalent circuit at this period is represented by Eq. (1) and the load current is represented by Eq. (2).

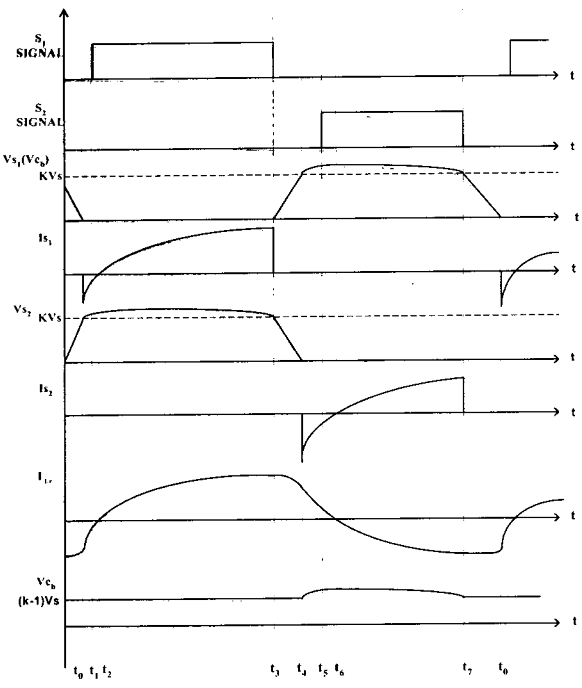


Fig. 4. Theoretical waveforms of the ACCE inverter mode.

$$-V_s + L_{eq}\frac{di_{eq}}{dt} + R_{eq} i_{Leq} = 0 \quad (1)$$

$$i_{Leq}(t) = \frac{V_s}{R_{eq}} + \left(i_{Leq}(t_0) - \frac{V_s}{R_{eq}} \right) e^{\frac{V_s}{R_{eq}} t} \quad (2)$$

(b) Turn-off state of the main switch (Mode 4)

After turn-off of the main switch, the load current flows through $L_{eq} \rightarrow R_{eq} \rightarrow C_r \rightarrow V_s$. Eq. (3) and Eq. (4) represent the voltage equation and the load current of the equivalent circuit at this period.

$$-V_s + L_{eq}\frac{di_{Leq}}{dt} + R_{eq} i_{Leq} + \frac{1}{Cr}\int i_{Leq} dt = 0 \quad (3)$$

$$i_{Leq}(t) = Ae^{\frac{a}{2}t} + Be^{\frac{b}{2}t} \quad (4)$$

where, $A = \dfrac{2V_s - i_{Leq}(t_3)\,R_{eq}}{2L_{eq}\sqrt{\left(\dfrac{R_{eq}}{L_{eq}}\right)^2 - \dfrac{4}{L_{eq}C_r}}} + \dfrac{i_{Leq}(t_3)}{2}$,

$$B = \frac{i_{Leq}(t_3)}{2} - \frac{2V_s - i_{Leq}(t_3)\,R_{eq}}{2L_{eq}\sqrt{\left(\frac{R_{eq}}{L_{eq}}\right)^2 - \frac{4}{L_{eq}C_r}}},$$

$$a = -\frac{R_{eq}}{L_{eq}} + \sqrt{\left(\frac{R_{eq}}{L_{eq}}\right)^2 - \frac{4}{L_{eq}C_r}},$$

$$b = -\frac{R_{eq}}{L_{eq}} - \sqrt{\left(\frac{R_{eq}}{L_{eq}}\right)^2 - \frac{4}{L_{eq}C_r}}$$

(c) Turn-on state of the auxiliary switch (Mode 5, 6, 7)

The voltage of main switch reaches the clamp voltage (kVs) and the antiparallel diode of auxiliary switch starts conducting. The auxiliary switch turns on under ZVS condition in Mode 7. The load current flows through $L_{eq} \rightarrow R_{eq} \rightarrow C_r \rightarrow V_s$ and $L_{eq} \rightarrow R_{eq} \rightarrow D_{S2} \rightarrow C_b$ as represented by Eq. (5). Two voltage equations and initial current conditions during this period are represented by Eq. (6), (7), (8) and (9) respectively.

$$i_{Leq} = i_{Cr} + i_{Cb} \quad (5)$$

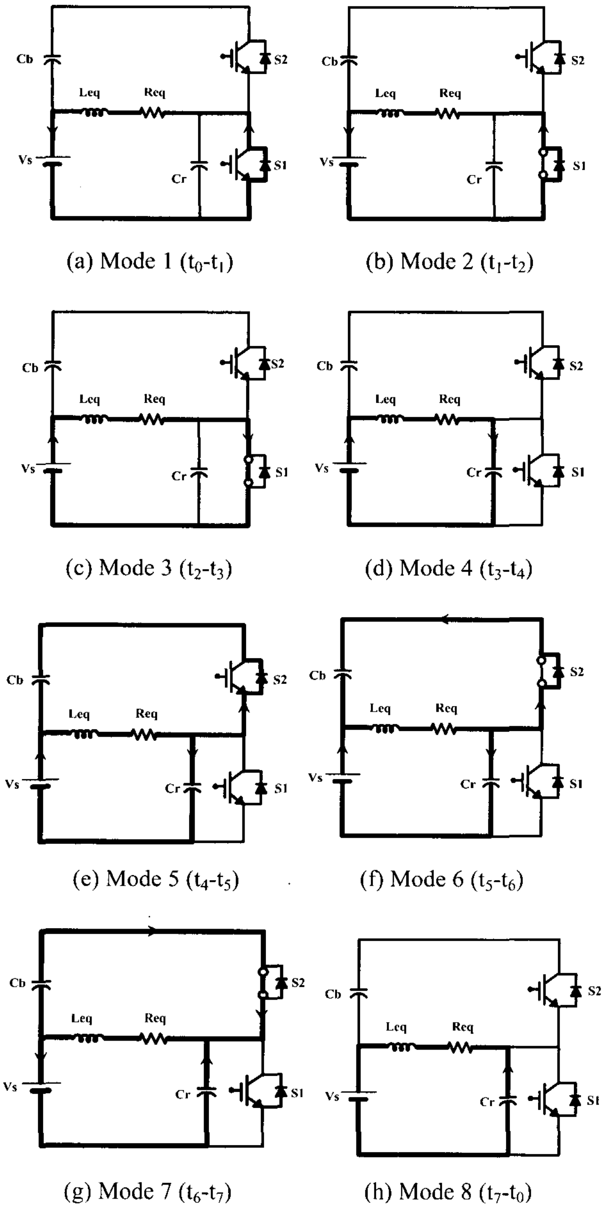


Fig. 5. Eight operating modes of the ACCE inverter mode.

$$-V_s + L_{eq}\frac{di_{Cr}}{dt} + R_{eq} i_{Cr} + \frac{1}{C_r}\int i_{Cr}dt = 0 \tag{6}$$

$$L_{eq}\frac{di_{Cb}}{dt} + R_{eq} i_{Cb} + \frac{1}{C_b}\int i_{Cb}dt = 0 \tag{7}$$

$$i_{Cr}(t_5) = \frac{C_b}{C_b + C_r} i_{Leq}(t_5) \tag{8}$$

$$i_{Cb}(t_5) = \frac{Cr}{C_b + C_r} i_{Leq}(t_5) \tag{9}$$

The currents of resonant capacitor and clamp capacitor are derived from Eq. (6), (7), (8), (9) as represented by Eq. (10) and (11). Eq. (12) represents the load current in this period.

$$i_{Cr}(t) = A' e^{\frac{a}{2}t} + B' e^{\frac{b}{2}t} \tag{10}$$

$$i_{Cb}(t) = A'' e^{\frac{a}{2}t} + B'' e^{\frac{b}{2}t} \tag{11}$$

$$i_{Leq}(t) = (A' + A'')e^{\frac{a}{2}t} + (B' + B'')e^{\frac{b}{2}t} \tag{12}$$

where, $A' = \frac{2V_s - i_{Cr}(t_5)R_{eq}}{2L_{eq}\sqrt{\left(\frac{R_{eq}}{L_{eq}}\right)^2 - \frac{4}{L_{eq}C_r}}} + \frac{i_{Cr}(t_5)}{2}$,

$$B' = \frac{i_{Cr}(t_5)}{2} - \frac{2V_s - i_{Cr}(t_5)R_{eq}}{2L_{eq}\sqrt{\left(\frac{R_{eq}}{L_{eq}}\right)^2 - \frac{4}{L_{eq}C_r}}},$$

$$A'' = \frac{2V_s - i_{Cb}(t_5)R_{eq}}{2L_{eq}\sqrt{\left(\frac{R_{eq}}{L_{eq}}\right)^2 - \frac{4}{L_{eq}C_r}}} + \frac{i_{Cb}(t_5)}{2},$$

$$B'' = \frac{i_{Cb}(t_5)}{2} - \frac{2V_s - i_{Cb}(t_5)R_{eq}}{2L_{eq}\sqrt{\left(\frac{R_{eq}}{L_{eq}}\right)^2 - \frac{4}{L_{eq}C_r}}}$$

(d) Turn-off state of the auxiliary switch (Mode 8)

Due to the turn-off of the auxiliary switch, the load current flows through $L_{eq} \rightarrow R_{eq} \rightarrow C_r \rightarrow V_s$. Eq. (13) and (14) represent the voltage equation and the load current respectively.

$$-V_s + L_{eq}\frac{di_{Leq}}{dt} + R_{eq} i_{Leq} + \frac{1}{Cr}\int i_{Leq}dt = 0 \tag{13}$$

$$i_{Leq}(t) = A''' e^{\frac{a}{2}t} + B''' e^{\frac{b}{2}t} \tag{14}$$

where, $A''' = \frac{2V_s - i_{Leq}(t_7)R_{eq}}{2L_{eq}\sqrt{\left(\frac{R_{eq}}{L_{eq}}\right)^2 - \frac{4}{L_{eq}C_r}}} + \frac{i_{Leq}(t_7)}{2}$,

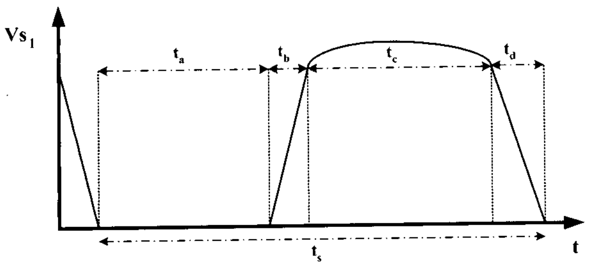


Fig. 6. The voltage of main switch in one switching cycle.

$$B''' = \frac{i_{Leq}(t_7)}{2} - \frac{2V_s - i_{Leq}(t_7)\,R_{eq}}{2L_{eq}\sqrt{\left(\frac{R_{eq}}{L_{eq}}\right)^2 - \frac{4}{L_{eq}C_r}}}$$

Fig. 6 shows the voltage waveform of main switch, S_1, during one switching cycle to calculate the clamp level (kVs).

The turn-off of the main switch makes the resonance between the resonant inductor, L_{eq}, and the resonant capacitor, C_r. When the voltage of the main switch reaches the clamp level (kVs), the anti-parallel diode of the auxiliary switch starts conducting and another resonance occurs through the resonant inductor, L_{eq}, the resonant capacitor, C_r and the clamp capacitor, C_b. Therefore, the voltage of the main switch is clamped to the constant voltage level (kVs). From Fig. 6, the clamp level can be given by Eq. (16) because the energy balance equation, which is calculated by Eq. (15), between input and resonant capacitor during one switching cycle becomes zero.

$$t_s V_s \cong \frac{1}{2} k V_s (t_b + t_d) + t_c \cdot k V_s \tag{15}$$

$$k = \frac{2t_s}{2t_c + t_b + t_d} \tag{16}$$

3. The Hybrid Control Scheme

The block diagram of the proposed hybrid control scheme is shown in Fig. 7.

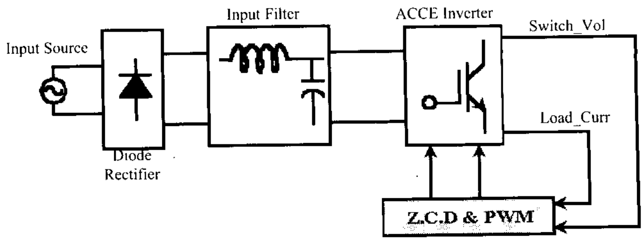


Fig. 7. The block diagram of the proposed control scheme.

It has two control loops that are the load current feedback and the voltage feedback of main switch respectively. The operation of ACCE inverter by feeding back voltage of main switch is determined as class-E inverter mode or ACCE inverter mode by comparing with the clamp level (kVs), that is to say, it means that the operation of the auxiliary circuit is able to be used or not. Therefore, main switch voltage is clamped to the clamp level (kVs) due to the operation of the auxiliary circuit. Another control loop, the feedback of the load current, is used to be sure of the ZVS of main switch since the ACCE inverter system with the proposed hybrid control scheme has two resonant frequencies by operating two different inverter modes. One is resonant frequency of class-E inverter mode, which is represented by Eq. (17) and the other is resonant frequency of ACCE inverter mode, which is represented by Eq. (18). Therefore, PWM through detecting of zero crossing of the load current is necessary to guarantee a stable ZVS operation although resonant frequency changes.

$$f_{rE} = \frac{1}{2\pi\sqrt{L_{eq} \cdot C_r}} \tag{17}$$

$$f_{rA} = \frac{1}{2\pi\sqrt{L_{eq} \cdot (C_r + C_b)}} \tag{18}$$

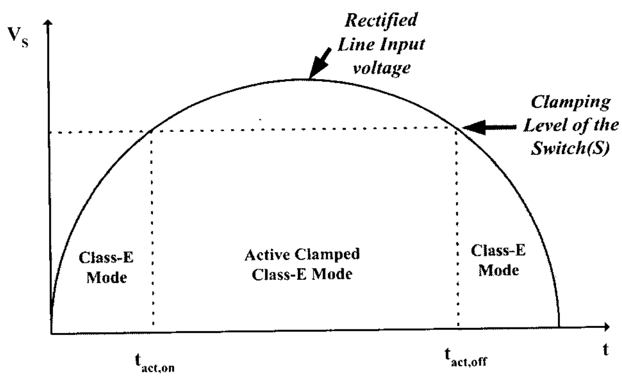


Fig. 8. Two operation modes of the ACCE inverter system with the proposed hybrid control scheme according to input voltage.

Fig. 8 shows two operation modes of the ACCE inverter system with the proposed hybrid control scheme according to input voltage.

The conventional ACCE inverter system clamps the switch voltage at all range of input voltage. As shown in Fig. 8, the ACCE inverter system with the proposed hybrid control scheme, however, doesn't clamp the voltage of main switch at low input voltage to increase output power. This is a very interesting feature of the ACCE inverter system with the proposed hybrid control scheme.

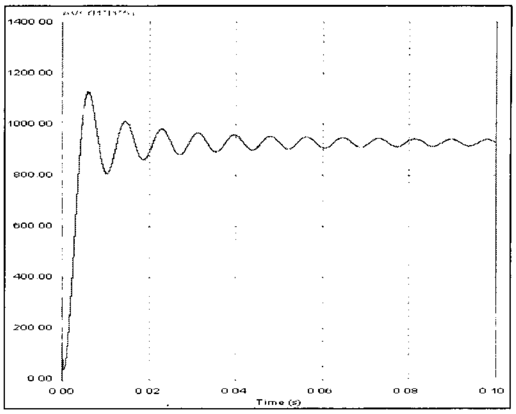
4. Simulation and Experimental Results

To verify the ACCE inverter system with the proposed hybrid control scheme, simulation and experiment were performed with same parameters as summarized in Table 1.

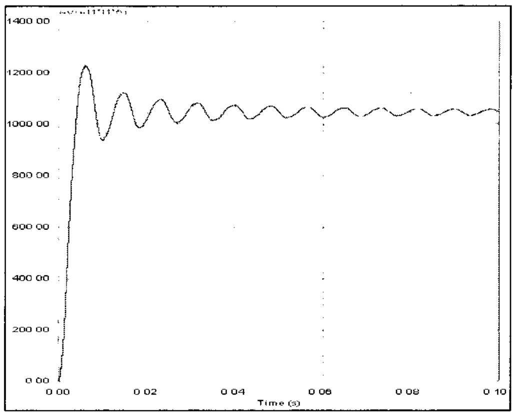
Main feature of the proposed control scheme using the ACCE inverter system is shown in Fig. 9. Fig. 9(a) shows the average output power with the conventional control scheme and Fig. 9(b) indicates the average output power with the proposed control scheme. From this figure, the proposed hybrid control scheme increases the average output power about 12% over that of the conventional control with same maximum peak voltage and current of the main switch.

Table 1. Utilized parameter for simulation and experiment of the ACCE inverter.

COMPONENTS		PARAMETERS
V_s	Input voltage	220 V_{AC}
f_s	Switching frequency	20 kHz
f_r	Resonant frequency	32.25 kHz
L_f	Input filter	TDK EI-70 750 μH
C_f	Input filter	2 μF
L_{eq}	Equivalent inductor	127 μH
R_{eq}	Equivalent resistor	5Ω
C_r	Resonant capacitor	160 nF
C_b	Clamping capacitor	800 nF
S	Main switch	IGBT F 90N60UFD
S_a	Auxiliary switch	IGBT F 90N60UFD



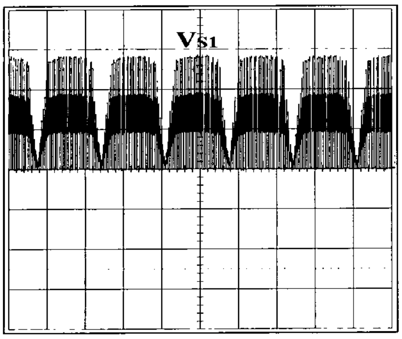
(a) Conventional ACCE inverter



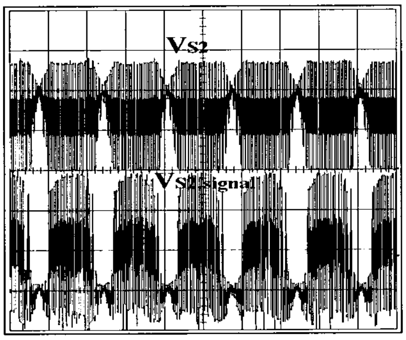
(b) ACCE inverter with the proposed hybrid control scheme

Fig. 9. Simulated result of average output power.

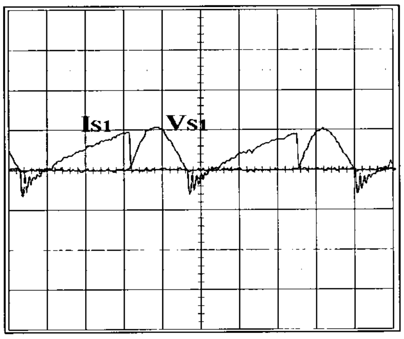
Fig. 10 shows the experimental results of the ACCE inverter system with the proposed control scheme. Fig. 10 (a) shows the voltage of main switch and Fig. 10 (b) shows the voltage and gate signal of auxiliary switch. They prove that the operation of the auxiliary circuit can be used or not according to the proposed hybrid control scheme, that is to say, the auxiliary circuit doesn't operate in order to increase the output power at low input voltage. However it operates to reduce the voltage stress of main switch at high input voltage. Fig. 10 (c) and fig. 10 (d) show the voltage and the current waveforms of the main switch, S_1, and the auxiliary switch, S_2 in case that the switch voltage is lower than reference switch voltage for clamping of the switch. From these waveforms, the ZVS turn-on of the main switch is ensured by the zero-current-detection of load current loop although resonance frequency is changed. Fig. 10 (e) and Fig. 10 (f) show the voltage and the current waveforms of the main switch, S_1,



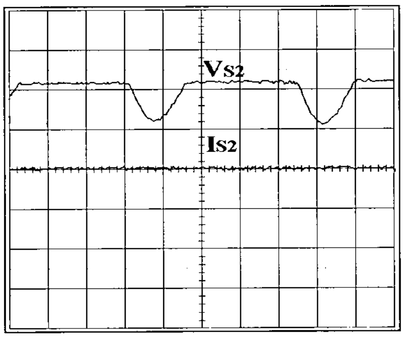
(a) V_{S1} (250V/div., time: 5ms/div.)



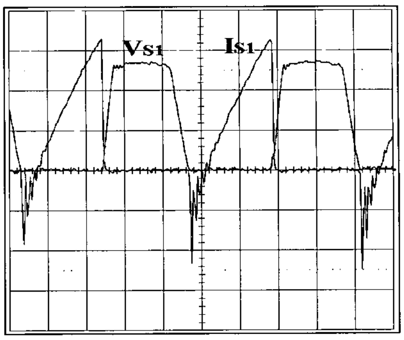
(b) V_{S2} (250V/div., time: 5ms/div.)
V_{S2}, signal (5V/div., time: 5ms/div.)



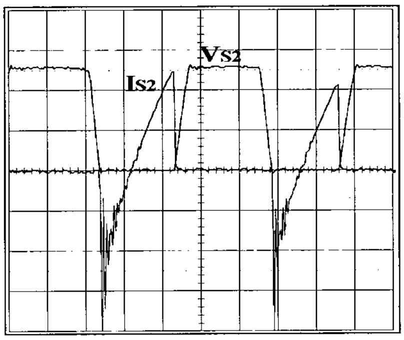
(250V/div., 10A/div., time: 10us/div.)
(c) V_{S1}, I_{S1} (below reference voltage)



(250V/div., 10A/div., time: 10us/div.)
(d) V_{S2}, I_{S2} (below reference voltage)



(250V/div., 10A/div., time: 10us/div.)
(e) V_{S1}, I_{S1} (above reference voltage)



(250V/div., 10A/div., time: 10us/div.)
(f) V_{S2}, I_{S2} (above reference voltage)

Fig. 10. The experimental results of the ACCE inverter system with the proposed control scheme.

and the auxiliary switch, S_2, at high switch voltage when compared with reference switch voltage. The proposed control scheme, also, does guarantee not only the ZVS turn-on of the main switch but also that of the auxiliary switch because of load current control loop.

5. Conclusion

In this paper, new ACCE inverter system with the proposed hybrid control scheme is presented to obtain higher output power than conventional ACCE control scheme for IH jar. Theoretical analysis and operation principles were described in detail. To verify the property of the ACCE inverter system applied the proposed control scheme, simulation and experiment were performed.

As shown by theoretical analysis, simulated and experimental results, the main features obtained are as follows:

- ♦ Increasing output power of ACCE inverter system.

- Reducing the voltage stress of main switch.
- Reducing the switching loss and EMI due to reduced switching of the auxiliary switch.
- ZVS turn-on for all active switches regardless of change resonant frequency.

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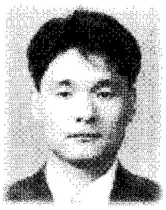

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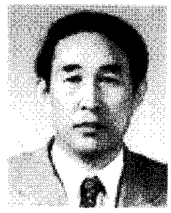

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Dr. hyun is a member of the IEEE Power Electronics, IEEE Industrial Electronics, IEEE Industry Applications, and IEEE Electron Devices Societies, the Institution of Electrical Engineers (U.K.), the Korea Institute of Electrical Engineers, and the Circuit Control Society.