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Inductive Heating Facility of Half-bridge Inverter Structure

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Abstract: - Nowadays the inductive heating technique is very popular in Taiwan, and this promoted research in this field directing to higher power, higher frequency, and higher efficiency as well. But most of the circuit structure in large capacity devices was adapted with Half-bridge or Full-bridge structure in Inverter. In this study, a half-bridge driven by fixed-frequency was implemented in a variable power, constant frequency inductive heating facility in which the circuit was adapted Resonant- Transition in Zero-Voltage-Switching, Clamped-Voltage (ZVS-CV). The power elements were selected Isolated Gate Bipolar Transistor-IGBT with 600 volts Voltage Endurance and 60 Amperes Endurance current while driving signal was switched by Pulse Width Modulation (PWM). The generating power was controlled by adjusting the turn-on timing of IGBT, in this way, the power factor of power-source side was highly promoted, and the driving signal was generated by TMS320F240 (DSP), so as well as detected the status of whole system with sampling in AD converter channels of DSP. Due to the design of this model the high performance was easily gained. The analysis of power change by adjusting Duty-cycle, the loading current waves, EMC under different operating frequency were verified and matched with the original theory through simulation with Is-Spice Software.

Key-Words: Resonant-Transition, Isolated Gate Bipolar Transistor, Pulse Width Modulation, Zero-Voltage-Switching, Clamped-Voltage

1 Introduction

Owing to the progress of semi-conductor components in recent decades, more power elements could be applied in products of higher-power device. So as well the increase of endurance of voltage and ampere of components prompted the rapid development of power electronics field. That leads to higher frequency, response, and efficiency performance of a larger capacity heating device. For instance, most of products in industry machineries were used the inverter technique such as AC inductive motors, non-brush DC motors, washing machine, inductive heaters, UPS, switching power suppliers, and sonar power system. ◦ Especially the popular application of inductive heater was in illustration of the development of industry. Since the heating methods such as gas or electricity in family would leak heat around the heater itself, the heater got lower energy transformed efficiency. The inductive heating method which uses rectifiers and high frequency inverter to convert 60Hz AC input current into 20~40KHz high frequency energy output to supply the inductive coils which would generate the inductive eddy current so as to heat the pan over coils.

Nowadays the power electronic technique is to implement the electronics into huge power circuits or systems. So to speak, it's a process how to deal with power transformation with semiconductor components. Electronic technique has been developed since the first Silicon Control Rectifier (SCR) was invented in 1956. Today power electronics can be divided into Traditional and modern stage. The former was mainly developed power capability with SCR such as fast-speed SCR, inversed-conduct SCR, bi-direction SCR etc. Not with standing the improvement with parameter as voltage, current, dv/dt, di/dt, and switching feature, yet there were many choke points such as lack of ways of up-grade running frequency. That led to add capacities, conductors, and some auxiliary switches in circuits, and led to improper size of products and in-application controlled frequency, and finally the new generation electronic technique was initiated.

The latest electronic technique has broken away the traditional constrains since new type components invented in 1980 such as power field-effect-transistor, insulated-gate field-effect-transistor (IGFET), isolated-gate bipolar transistor (IGBT), Power Metal-Oxygen-Silicon FET (Power MOSFET) etc. The new components advocated Pulse-Width-Modulation (PWM), zero voltage, zero current, and switching resonance [2,8]. Furthermore, those new type components own superiorities such as integrated, high controlled frequency, fully-controlled circuit, digital control, upgrading switching frequency, decreasing audio-frequency noise lower current ripple and cost down.

The most easily damaged components in power electronic driver circuits are switching ones, and under the consideration of both high voltage and current endurance and easily driven, the related design were mainly taken advantage of Insulated Gate Bipolar Transistor-IGBT and Power MOSFET. IGBT owns features of high speed, driving capability, and input resistance, so was viewed as most proper for high power switching components. In addition, it also owns high voltage endurance at off condition while loading high current at on condition. But IGBT has two defects, one is huge off current and longer delay time that lead to much waste power and the other is latch-up effect, that would causes out of control of Gate polar or even complete damage to components. Sum up, the purpose of this study is to design a high power stable heating device with safety and intelligence. Generally speaking, An intelligent and stable high power magnetic inductive heating facility with IGBT as switching components would provide well protection for driver circuit to avoid damage of components even under any troubleshooting including incorrect programming, and this performance would be the motivation of this study.

Since magnetic inductive heating facility belongs to application of high frequency electronic power components which combine of both inerter and technique of switching so as to convert low frequency DC power into high frequency AC power. Finally, crossing the coils with changed magnetic field and generating eddy current on the surface of ovens, in the process, through coupled magnetic field to convert electric energy into magnetic energy, further more convert magnetic energy into heat transferred to loads to accomplish heating effect. But, the higher frequency of switching components is, the more switching lose is. Driving signal couldn't control on and off of IGBT on account of latched effect resulting from over-loading and noise, and this condition led to damage of IGBT themselves and larger stress of components resulting from current or voltage glitches. So how to design a high frequency, power, and performance inverter with Zero-Voltage-Switching (ZVS) is the purpose of this research.

The structure of this paper was called Class-D half-bridge resonate Inverter [1], and the resonation circuit has both resonated interval and non-resonated interval during in a switching period, and this resonated method was classified into to Zero-Voltage-Switching, Clamped-Voltage, (ZVS-CV) [3] conversion circuit. The method in this paper is to adopt soft switching so as to get current resonated and ZVS, which would reduce the switching loss of IGBT and promote the system efficiency. Furthermore, we drove gate polar of IGBT with symmetrical Pulse Width Modulation (PWM) signals to reduce current harmonic of supply power and improve its power factor.

2 Study Motivation

Most traditional inverter adopted hard switching, and it would increase loss of power electronic components and couldn't run under high power and frequency condition. Moreover, even resulted in increasing harmonic of supply power and damage of IGBT because of overheat. This paper tried to adopt soft switching strategy of series resonance and the designed structure is Class-D Half-bridge series resonance inverter. Owing to simple structure and high efficiency, the resonance current was approximate to sine-wave as to improving power factor and efficiency of whole system. From literature review [9], inductive heating own superiority as (1) fast heating process (2) safety (3) low pollution (4) accurate temperature control (5) proper power control (6) no-limitation by environment. So how to convert DC current rectified from AC power supply to high frequency AC current needed by load and produce less harmonic during conversion process so as to cut down the loss of IGBT and finally design a high power, easily driven, high efficient heating technique of inverter taken advantage by inductive heating method that is superior to traditional ones was the main motivation of this study.

3 Literature Review

There were three main direction of power electronics research as follow: (1).Power elements such as IGBT, Power MOSFET, and GTO. (2) Circuit topology such as Half-bridge, Full-bridge. (3) Control technique such as PWM, PAM, PFM, and PDM.

Present research papers for inductive heating most focus on full-bridge [9] or half-bridge [1,5] and the driving signals were used Pulse Width Modulation (PWM), and Sinusoid Pulse Width Modulation (SPWM). The driving types can be divided into Symmetric and Non-symmetric [7,8]. The switching methods are Zero-voltage and Zero-current. The switching frequency are Fixed-frequency switching and Variable-frequency to adjust output power. As to the power control are PWM with fixed-frequency control and SPWM technique in which the switching ON timing was adjustable to control power output. The other one is Pulse Frequency Modulation (PFM) [2] that is varying the switching frequency according to load variety, and in this way, switching frequency would automatically correspond to the change of resonated frequency to get the maximal power output.

As to now, the control method for half-bridge structure is using variable-frequency with fixed turn-off timing on IGBT [13], and this method could protect switching components. But the power is limited due to being limited of turn-off current. The switching frequency of PFM [2] would vary according to the varying of load to get maximal power and generally adopted variable power constant frequency (VPCF), fixed-frequency PWM [11,12]. In literature [1], the switching way adopted that switching frequency was more than resonated frequency, so we could get to the effect of ZVS. As to the control signals of PWM have symmetric and non-symmetric. It was easy for symmetric way to control power output that most multi-half-bridge control structure will adopt this method [4].

The control method in full-bridge structure was phase-shifting ZVS inverter which uses the stray capacity on IGBT and stray inductance in circuit to achieve the ZVS and soft switching to low down the switching loss, so would the full-bridge structure use fixed-frequency to achieve phase-angle shifting of output voltage to control the power output. In the literature [1], the inverter adopted half-bridge with forced switching, in which the switching frequency is more than resonated frequency, and there are many superiority as follow: (1) Zero Voltage Switching could low down the switching loss of IGBT. (2) Excluding the reversed current of flywheel diode could cost down the components. (3) Power control range becomes larger, and this condition is suitable for larger variety of power control. (4) Using two resonated capacities could reduce the effective value of ripple current on DC-LINK capacity and increase power fact of supply power. (5) It could provide driving signal with 50% duty-cycle. In the literature [2], it presented PFM technique as control strategy for power control. The control theory is basically on how step after the load change, that means the control circuit would feedback the loading current and then vary frequency that steps after the resonated frequency to achieve the optimal power output point. This kind of varying system switching frequency to control power output is most suitable for heating iron pans made of magnetic-admittance materials and for aluminum pans made of non-magnetic-admittance materials.

This paper adopted the structure presented in literature [1], in which we selected fixed switching frequency, and the reason why we selected this way was as follow: (1) it is easy to design the EMI filter and minimize size of filter. (2) when we developed multi-oven in one system, the noise generated by switching frequency among ovens could be minimized.

We learned that there was no difference of the efficiency of inverter performance between fixed DC voltage and non-fixed voltage. But the current flowed into fixed DC voltage inverter and IGBT is larger than that of non-fixed DC voltage inverter and this would upgrade the selection of components even would increase the extra cost. So we adopted non-fixed DC voltage inverter as our research direction.

From literature [1], the Q value in fig 9 was affected by combined resistance. If the pan existed and had the better magnetic-admittance, the value of its resistance would be larger and result in smaller Q value. If switching frequency were larger than resonated frequency (fs>fr) and the Q value were very small, the change range of switching frequency would be larger and lead to broader range of power control. So in this paper we adopted the method that switching frequency was larger than resonated frequency. It would let circuit operate in high power under ZVS and cut down the turn-on loss on IGBT which would be embedded with clipping resonated circuit to cut down turn-off loss of IGBT.

4 Research Method & Design

Since the switching way of IGBT and frequency were the key factor that affected the circuit operation, we first used Is-Spice to simulate the circuit function and analyze the wave of half-bridge circuit structure driving with set driving signals including Symmetric and non-symmetric PWM, SPWM. Then comparing the current flowing through IGBT and analyzing current wave on coils and noise under fixed power output to learn the whole theory and adjusted the related parameters in the circuit according to the wave change. Then we experimented with the RLC series resonation in order to learn the switching loss generated from the switching signals for IGBT, and found solution of how the noise low down and power factor become better to promote the efficiency of power system. Finally, we designed the resonation capacities and inductance in the circuit to decide (a) power output (b) RMS value of output current (c) system switching frequency. Then we designed Clamped-voltage slow-resonated circuit to change ON and OFF timing of IGBT so as to low down switching loss during switching of IGBT and restrain over-voltage of IGBT that generates high dv/dt doing damage to IGBT. We judged whether the pan really exist or not by response of RLC circuit and whether the pan was taken away or not by calculate the power change through voltage and current sampled from AD channel of DSP. We used photo-couple circuit to isolate driver circuit with IC (HCPL-3120) and designed voltage, current over-loading and overheating circuits after learning the dynamic and static features of IGBT. Meanwhile we adopted DSP (TMS320F240) to develop the core program of whole system to generate PWM signal needed by controlling IGBT and CPLD as protecting PWM circuit to avoid simultaneously ON of up-IGBT and bottom-IGBT that would result in damage of IGBT.

5 Simulation & Analysis of inverter circuit

When DC power supplies to AC load, it must process DC to AC converting. This function accomplishing DC to AC converter is DC-AC conversion circuit or called inverter. Supposed we classify inverter with feature of DC power, it could be divided voltage-type and current-type, and in this paper we adopted the former.

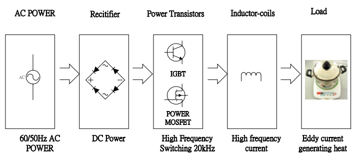

Fig. 1 Structure of Half-bridge Resonated Heating-process

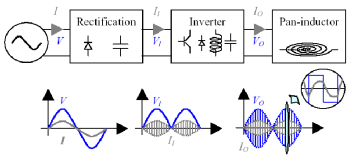

Fig. 2 the voltage wave during Resonated Heating-process

In Fig. 1, AC power (110V/220V, 60Hz/50Hz) converted into half-cycle positive AC power by rectification, and the power was converted into smooth DC power after passing through LC low-pass filter which coupled with a high-voltage endurance shunt capacity. Finally, the inverter generated a high frequency current by switching of IGBT or Power MOSFET and generated a changed magnetic-field with electric-magnetic induction, which would induct cross-over inductor-coils and generated eddy-current on the surface of magnetic materials to accomplish heating effect. Fig. 2 shows the voltage and current wave change during electric energy converting into heat energy.

As Fig. 3, in this paper we adopted turn-on-off resonation converter, which generated high frequency AC signals for load by LC resonation pool with switches turning on and off. DSP generated driving signal and judged present condition of system by voltage feedback signals generated by sampling from power current and load current that flowed through Current Transformer (CT). The primary function of EMI circuit is to get rid of noise generating from high frequency switching as well as from AC power.

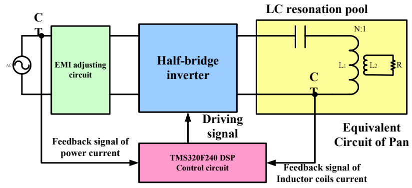

Fig. 3 the Development Chart of System

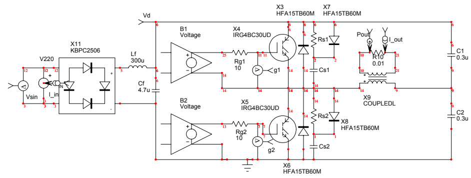

Fig. 4 the simulation circuit of main system

In Fig. 4, the design of the half-bridge inverter simulation circuit including selection of gate driving resistor of IGBT and clamped RCD slow-resonation circuit could decide output power, switching frequency, the value of resonation capacity and inductance which combined the half-bridge inverter. Then it will convert non-smooth DC voltage into high frequency current for load by high frequency PWM switching signals.

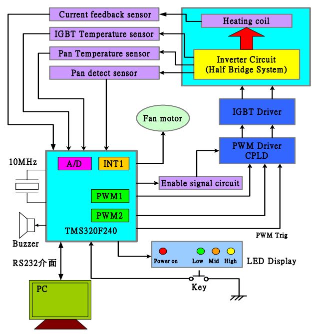

Fig. 5 system development structure

In Fig. 5, we used DSP to generate the driving signals for IGBT and design protection circuit with CPLD to prevent the upper and lower IGBT from switching ON simultaneously even burn down IGBT. On the other hand, through external interrupt signals CPLD would detect the load condition (whether there is a pan or not) and send back the detected signal into DSP; further more, it also feedback sampled temperature, voltage, current signals into 10 bits AD channels inside DSP to avoid system in danger condition. All the immediate information sampled by DSP would send to PC terminal through

RS-232 interface to let user learn the power change situation on line immediately.

6 Experiment Results

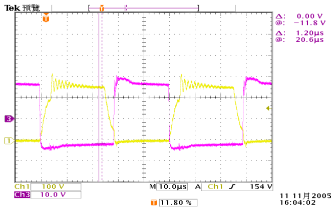

Fig. 6 The lower IGBT control signals without at soft-switching

In Fig. 6, the pink color (channel 3) wave pointed out the driving signal of IGBT, ranged +15v ~ -11v, frequency 20K Hz. And the yellow color wave (channel 1) was voltage between collector and emitter of IGBT (Vce), it's about 297V. From the figure, it was obvious that if the Vce hadn't descended to zero while the driving signal was ON, this meant IGBT was not precisely operating on soft-switching point and that's why so large harmonic appeared on Vce wave, in addition, the slop of Vce became larger at switching-point and this meant dv/dt became larger.

Under same condition, in Fig. 7, it was obvious that if the driving signal was ON while dv/dt went down to zero, the harmonic on Vce wave was less than that in Fig. 6 and slop kept smooth leading to the output power became stable. This meant the IGBT was under controlled at precise soft switching-point. The result was shown in Fig. 7.

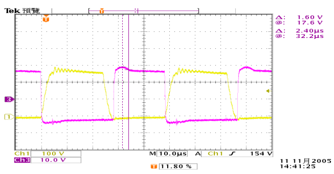

Fig. 7 The lower IGBT control signals at soft-switching

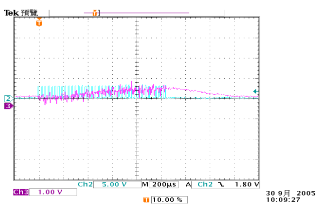

Fig. 8 Inductor-coils current wave without pan

The blue color pulses (channel 2) was the shooting pulses designed to generate the driving signals for lower-IGBT and the red wave (channel 3) was inductor-coil current wave converted by current transformer (CT). Fig. 8 showed inductor-coil current wave without pan and Fig. 9 showed inductor-coil current wave with pan on heating stove. Comparing the two figures, we learned that the peak value of inductor-coil current were quite different, so we could detected whether there was a pan on stove or not by detecting peak value of voltage gained from converting inductor-coil current to voltage through CT. The circuit was shown in Fig. 10.

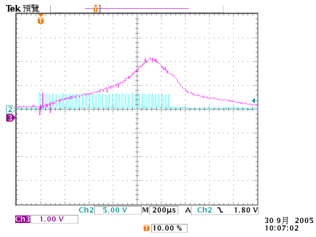

Fig. 9 Inductor-coils current wave with pan

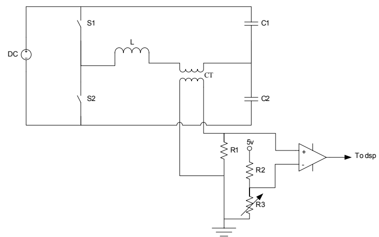

Fig. 10 Detect circuit for condition of pan

7 Conclusion & Suggestion

In this study, a half-bridge driven by fixed-frequency was implemented in a variable power, constant frequency inductive heating facility in which the circuit was adapted Resonant-Transition in Zero-Voltage-Switching, Clamped-Voltage (ZVS-CV). After simulation with Is-Spice and practical experiment, we gained the conclusion as following : (1) In the heating process, if we took away the pan, the combined resistance and inductance in the circuit would decrease that caused Q value increase and make switching frequency near to resonated frequency, and the pan-inductor-coil current instantly rose upward. Provided that the Ic of IGBT were more over than Ic maximum, the IGBT would occur to latch effect that led to out of control of power or even damage to IGBT themselves. So the most important design factor of software is the detecting of putting away of the pan. It is necessary to immediately judge pan's being put away and stop the PWM control signal to avoid the damage of IGBT.

(2) The detected method for pan putting away in this paper utilized the current transformer to decade current flowing through primary winding and convert into the voltage signal with resistors and capacities, finally amplified the signal with OP to 0~5 volt level which would sampled by DSP AD channels, and the current change amount would be used to compare with the former sampled current and then judge whether the pan was put away or not.

(3) The practical design of large-scale power resonated pan can be divided into three types: (a) to

pull up the primary power supply (b) to pull up the capacities value on DC BUS (c) to decrease inductance of pan-inductor-coil or enlarge the resonated capacity. But the inductor-coil is made of winding copper and it couldn't be too thin; otherwise, the coil would be burnt down because of overheating, so the inductance can't be decreased too much.

(4) The duty-cycle must increase gradually when upgrade the fire of stove to avoid doing damage to IGBE because of high di/dt which causes fast rising of current of IGBT rises quickly.

(5) The system should immediately detect the putting away of pan and turn off the PWM control signal lest the current of resonation slot should suddenly increase to cause the latch effect of IGBT, so there must be hardware or software design to detect the putting away of pan.

(6) The practical design for high power inductive heating devices should focus on voltage-proof and current-proof class of components, especially the layout should separate the power wire and signal wire to avoid the noise generated from power lines.

(7) The clamped RCD slow resonated circuit should be near to IGBT as could as possible when layout to avoid generating stray inductance that would cause high di/dt resulting in burn down of IGBT.

(8) Restraining the stray oscillation generated by high frequency switching of IGBT has three methods as follow: (a) Shortening the pin wire of gate polar of IGBT as could as possible (b) Using ferrite bead (c) Setting series resistor onto gate polar of IGBT.

(9) The strategies preventing the system from operation trouble-shooting are as follow: (a) Reducing stray capacities between driver circuit and ground. (b) Low down the resistor of driver circuit (c) Up-grade the rated voltage of driver circuit.

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