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Asymmetrical Duty Cycle Controlled Edge Resonant Soft Switching High Frequency Inverter for Consumer Electromagnetic Induction Fluid Heater

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Original scientific paper

This paper presents a new electromagnetic induction eddy current-based spiral type dual packs heater using a high frequency resonant inverter or the induction heating type heat exchanger, which is more suitable and acceptable for the consumer power applications. In addition, the proposed active voltage clamp edge-resonant soft switching PWM high frequency inverter using IGBTs can operate under a principle of the zero voltage soft commutation scheme. This inverter is developed for a high efficiency induction heating (IH) hot water producer or IH boiler and super heated steamer packed partially inside a variety of pipeline plants. This innovative consumer power appliance using soft switching PWM high frequency inverter, designed for the IH fluid heater, is evaluated and discussed on the basis of simulation and experimental results.

Key words: high frequency inverter, active voltage clamping, edge resonance zero voltage soft switching PWM, induction heating, dual packs heater, hot water producer and steamer

1 INTRODUCTION

In recent years, the electromagnetic induction eddy current-based fluid heat energy processing devices and systems using a variety of voltage source type and current source type high frequency inverters, which are based upon load resonant, edge resonant circuits, have attracted special interest [1–4]. The high efficiency, safety, cleanliness, compactness in volumetric size, rapid heating of the induction heated dual packs fluid heating devices using the voltage source active voltage clamped edge resonant high frequency inverter can be achieved for specific high power applications in industry and consumer fields.

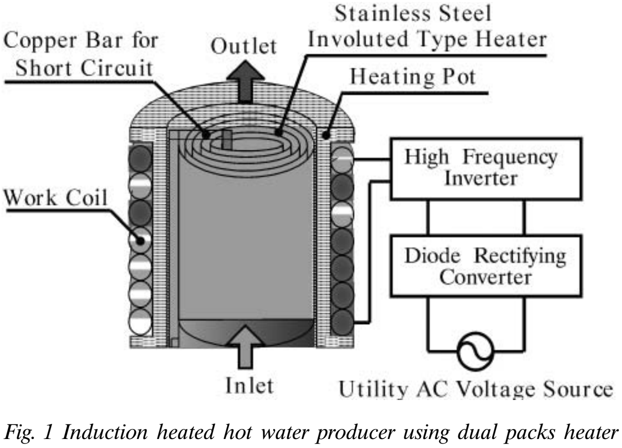


Fig. 1 Induction heated hot water producer using dual packs heater

This paper presents a new conceptual energy saving type electromagnetic induction eddy current-based fluid dual packs heating device inserted inside the pipeline systems, which is directly driven and controlled by an active voltage clamped type zero voltage soft switching PWM high frequency inverter using IGBTs. This industry and consumer use appliances as electromagnetic induction heated boiler are practically developed and evaluated on the basis of experimental and simulation results.

2 ELECTROMAGNETIC INDUCTION EDDY CURRENT HEATING-BASED HOT WATER PRODUCER

A novel prototype structure of an electromagnetic induction eddy current-based dual packs type fluid heating device, inserted into the fluid pipeline transportation is schematically depicted in Figure 1. This innovative energy conversion device called induction heated dual packs fluid heater in new generation is composed of an induction heating (IH) exchanger or induction heated dual packs fluid heater as IH boiler, air cooling working coil made of litz wiring, non-metal fluid heating vessel and voltage source edge resonant soft switching PWM high frequency inverter with low cost passive type PFC rectifier composed of diode rectifier and non-smoothing LC filter. The new product of the spiral type electromagnetic induction eddy current-based heat exchanger or dual packs fluid heater as a compact IH hot water producer and steamer using high frequency inverter in Figure 1 is practically designed under the following specific conditions:

a. Uniform temperature distribution using spiral structure heater with end cupper bar ring.
b. Wide heating surface in the compact vessel.
d. No erosion because of contactless.
e. No thermal deformation for high temperature use.
f. Small heat capacity because of the thin stainless steel sheet.

The new conceptual induction heater made of spiral type non-magnetic and conductive stainless steel SUS316 plate inserted into the heat proof non-metal heating vessel is demonstrated originally. It has an involuted IH heater structure with a short circuit due to the copper end ring to realize quick temperature response and uniform temperature distribution. This IH dual packs fluid heating device is composed of the spiral stainless steel plate assembly (see Figure 1) and its outside edge point is directly connected to the inside edge point by the copper bus bar. In this new heater structure, it is possible to achieve a uniform temperature distribution of this induction eddy current heated dual packs heater as a heat exchanger. In general, it is actually difficult to form the spiral type heater structure toward its center. In case of rolling up to its center, effective heating surface increment could not expect substantially. But if no obstacle is inserted in the center of spiral structure type IH heater, heat exchanging efficiency of this IH dual packs heater decreases because a large majority of heated liquid flows through the center. To improve reduced heat exchanging efficiency, the obstacle made of cylindrical polycarbonate material is inserted into the center of the spiral structure. The physical size and geometric shape of this induction heated dual packs fluid heating device is designed as illustrated in Figure 2.

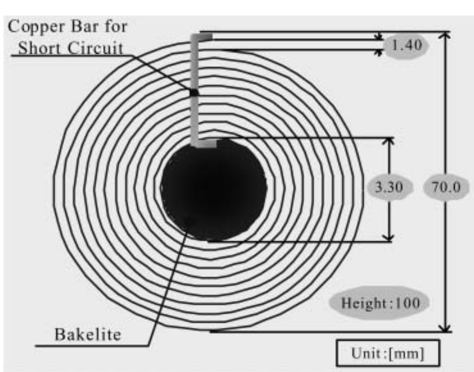


Fig. 2 Upper view of involuted type induction heating dual packs heater

3 ACTIVE CLAMPING EDGE-RESONANT ZVS-PWM HIGH FREQUENCY INVERTER

3.1 Circuit Description

Figure 3 shows a high frequency resonant inverter circuit topology used for the IH fluid heater. This inverter can operate under the condition of zero voltage soft switching (ZVS) commutation and constant frequency asymmetrical pulse width modulation (PWM) control strategy or duty cycle control implementation for output power regulation scheme of this inverter. This high frequency edge resonant PWM inverter using IGBTs has some advantageous points such as wide soft switching operation range, constant frequency PWM control, wide voltage regulation range, low peak voltage stress for the power switching devices (IGBTs). This power electronic appliance in the next generation is newly developed and implemented for IH dual packs type hot water producer and steamer. In Figure 3, this edge resonant ZVS-PWM inverter is illustrated, which has an equivalent load circuit represented as the transformer circuit model of IH fluid device.

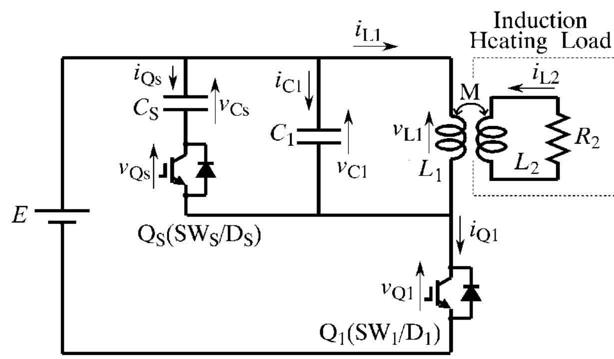
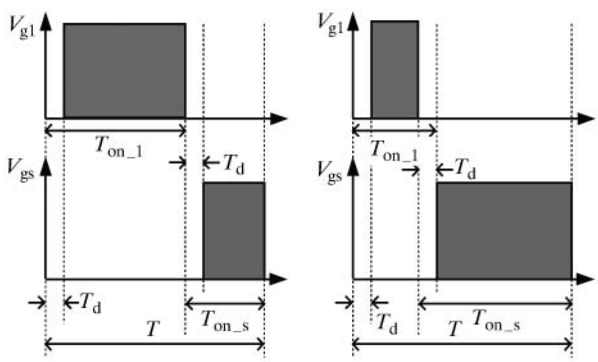


Fig. 3 Active voltage clamped edge resonant ZVS-PWM high frequency inverter using IGBTs

3.2 Gate Pulse Control Implementation

Figure 4 illustrates the asymmetrical PWM based gate pulse timing sequences for this edge resonant ZVS-PWM inverter using the main and auxiliary power switches; IGBTs. These voltages pulse trains are supplied to the gate parts of the power semiconductor switching blocks; Q_1 (SW_1&D_1) and Q_S (SW_S&D_S). The duty factor defined as $D = T_{on-1}/T$ acts as a control variable for the continuous power regulation of this high frequency edge resonant inverter operating at a constant frequency. The full power is delivered to the induction heating load when the conduction time T_{on-1} including the dead time T_d of the main power switch SW_1 of Q_1



a) in the case of large D
V_{g1}: Gate pulse for SW_1
V_{gs}: Gate pulse for SW_s
T: One cycle time for high frequency inverter

b) in the case of small D
T_{on_1}: Conduction time for SW_1
T_{on_s}: Conduction time for SW_s
T_d: Dead time
D: Duty factor ($=T_{on\_1}/T$)

Fig. 4 Asymmetrical PWM gate voltage pulse signal sequences

is to be lengthened as indicated in Figure 4.a. On the other hands, when the low power is required to the load, the conduction interval is to be shortened as indicated in Figure 4.b.

3.3 Steady-State Operation of Edge Resonant Soft Switching PWM Inverter

Figure 5 represents the equivalent circuits for each operating mode of this edge-resonant ZVS--PWM inverter shown in Figure 3. Its operation in steady state is described as follows:

<*Mode 1*> Mode 1 is the time interval when the main active power switch SW_1 of Q_1 is turned on. The DC source supply voltage E is applied on the induction heating load represented by the transformer circuit model. When SW_1 is turned off with ZVS, the mode 1 moves to the mode 2.

<*Mode 2*> After the active power switch SW_1 of Q_1 is turned off, the resonant current i_{L1} flows through the resonant capacitor C_1. The inductive energy is delivered to the resonant capacitor C_1. When the voltage across C_1 is equal to V_{CS}, the diode D_S of the auxiliary switching block Q_S conducts and the mode 2 moves to the mode 3.

<*Mode 3*> The current i_{L1} flows through the lossless capacitors C_1 and clamp capacitor C_S and the peak voltage applied to the active power switch SW_1 is clamped. When the current through D_S of Q_S is equal to zero, the auxiliary power switch SW_S is turned on.

<*Mode 4*> During the time interval in mode 4, a direction of i_{L1} reverses. In this mode 4, the peak voltage applied to the main active power switch SW_1 is also clamped to a certain finite value in accordance with the voltage clamping capacitance. After SW_S of Q_S is turned off, the mode 4 moves to the mode 5.

<*Mode 5*> After SW_S is turned off with ZVS, the resonant current flows through C_1, L_1, L_2, R_2 and M or R_a and L_a with the relation of L_1, k, τ. The energy stored into L_1 is delivered to C_1. If the voltage across C_1 is over E, the diode D_1 of the main switching block Q_1 conducts. Then, the mode 5 moves to the mode 6.

<*Mode 6*> When non-resonant current i_{L1} is equal to zero, D_1 of Q_1 is tuned off naturally and the main active power switch SW_1 is turned on, the mode 6 moves to the mode 1.

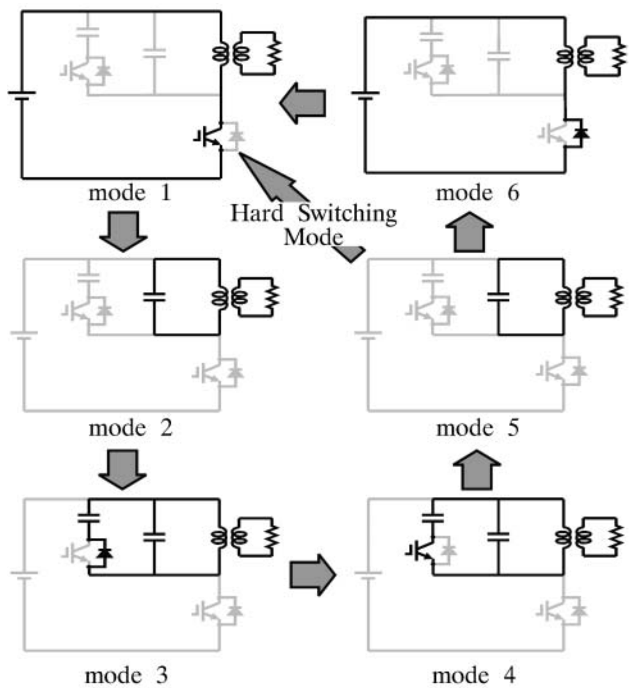


Fig. 5 Mode transitions and equivalent circuits

3.4 Switching Voltage and Current Waveforms

Figure 6 gives the steady state switching voltage and current simulation waveforms of Q_1 (SW_1&D_1) and Q_S (SW_S&D_S) under the zero voltage soft switching condition with $D=0.5$. In Figure 6, both of the main active power switch Q_1 and the auxiliary active power switch Q_S can completely achieve soft switching commutation. Besides, this high frequency edge resonant inverter can clamp an excessive peak voltage applied to the main switch in mode 3 and mode 4. This edge resonant inverter in steady state includes periodically repeated operation with 6 modes. Figure 7 represents duty cycle D vs. input po-

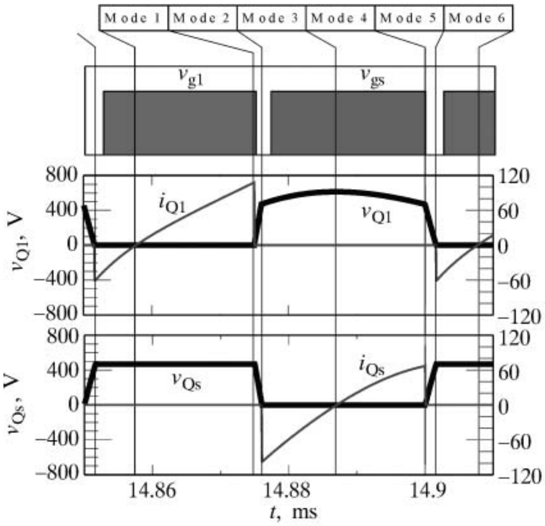


Fig. 6 Steady state switching voltage and current waveforms

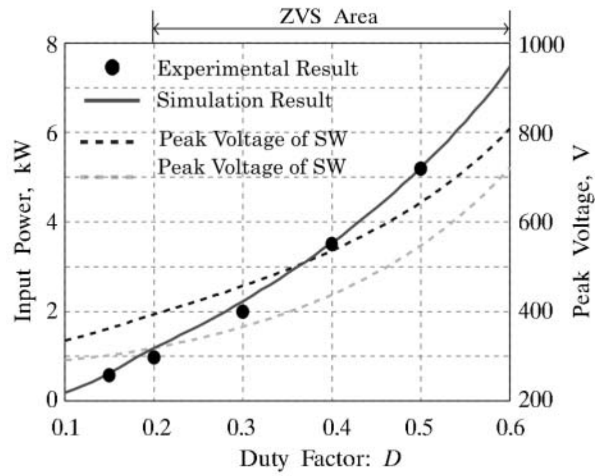


Fig. 7 Duty factor vs. input power and peak voltage characteristics

wer regulation characteristics and peak voltage characteristics for a new product of electromagnetic induction eddy current heating-based hot water producer under a constant frequency asymmetrical PWM control strategy. Observing this figure, it is clearly proved that the inverter output power can be continuously adjusted in accordance with Duty Factor D determined by PWM as a control variable.

4 Experimental Results and Discussions

4.1 Experimentally Produced Hot Water Producer

Table 1 indicates the practical design specifications and circuit parameters of the feasible electromagnetic induction eddy current heating-based hot water producer driven by the voltage source edge-resonant ZVS-PWM soft switching high frequency inverter using the IGBT modules.

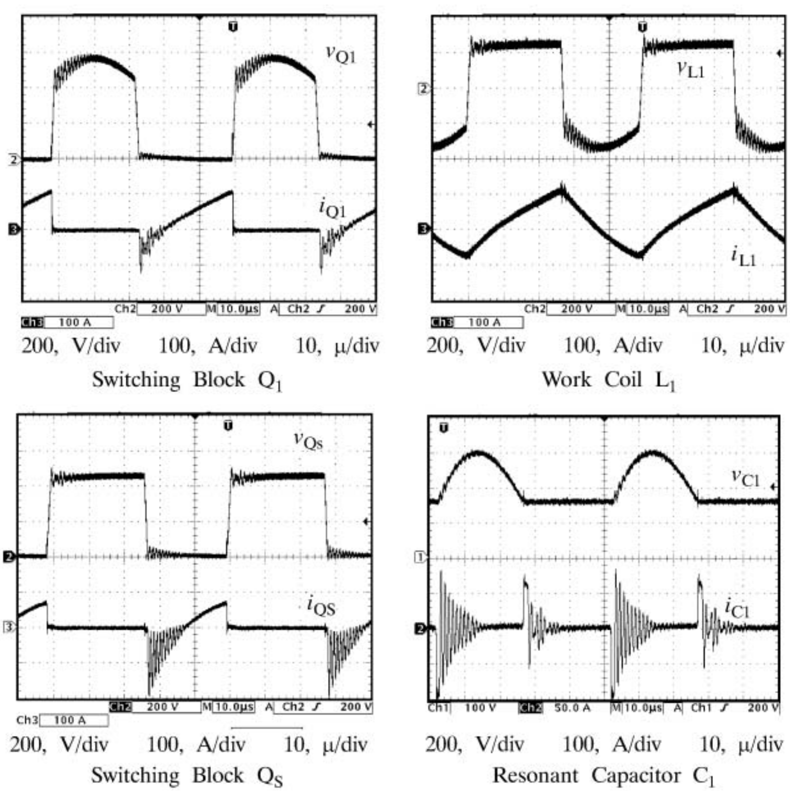


Fig. 8 Experimental voltage and current waveforms

Table.1 **Design specifications and circuit parameters**

Item	Symbol	Parameter, value
DC source voltage	E	200, V
Switching frequency	f	20, kHz
Quasi resonant lossles capacitor	C_1	0.18, μF
Active voltage clamped capacitor	C_s	3.96, μF
Working coil	L_1	50.9, μH
Electromagnetic coupling coefficient	k	0.693
Load time constant	τ	9.63, μs

Remarks: $k = \dfrac{M}{\sqrt{L_1 L_2}} = \sqrt{\dfrac{R_1^2 + \omega^2 (L_1 - L_a)^2}{\omega^2 L_1 (L_1 - L_a)}}$,

$\tau = \dfrac{L_2}{R_2} = \dfrac{L_1 - L_a}{R_a}$.

Figure 8 depicts the steady state observed switching voltage and current waveforms of Q_1 (SW_1&D_1), Q_S (SW_S&D_S), L_1 and C_1 under the condition of $D=0.5$. Besides, it is proved that this voltage-fed edge-resonant ZVS-PWM high frequency inverter can completely work under zero voltage soft switching operation for wide ranges of asymmetrical duty cycle control scheme ($0.2<D<0.9\cong 1.0$). This edge resonant PWM high frequency inverter can clamp an excessive peak voltage applied to the main active power switch because of the effect of the witched capacitor (Q_s and C_s).

4.2 Temperature Characteristics of IH Dual Packs Heater Type Hot Water Producer

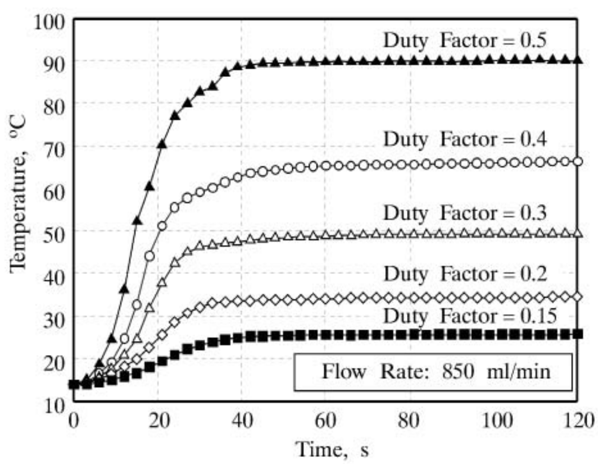


Fig. 9 Fluid temperature characteristics of induction heating dual packs heater type hot water producer

Figure 9 illustrate temperature characteristics of the induction heated hot water producer and steamer using high frequency inverter setup in experiment. It is noted that the edge resonant PWM inverter type consumer appliance using spiral type induction heating exchanger in the clean industry and consumer pipeline system can heat more rapidly and efficiently than conventional gas combustion type or sheathed wired heating type heat exchangers.

5 Conclusions

In this paper, the novel electromagnetic induction eddy current heating-based dual packs fluid heater type hot water producer, steamer and super heated steamer using voltage-fed edge-resonant PWM high frequency inverter has been successfully proposed for consumer power applications and demonstrated from a practical point of view. In addition to this, an active voltage clamped edge-resonant ZVS-PWM high frequency inverter using the IGBTs, which can efficiently operate under a zero voltage soft commutation on the basis of asymmetrical duty cycle control strategy. The performances of the induction heating dual packs fluid heating device driven by this edge resonant inverter was evaluated and discussed herein. The effectiveness of this new product used in next generation was proved on the basis of the feasible experimental data. This induction heating dual packs fluid heating appliances for consumer power electronics could be more cost effective than conventional gas combustion or sheathed wired heating type ones.

LIST OF SYMBOLS

C_1 edge resonant lossless snubbing capacitor
C_S active voltage clamped capacitor
$Q_S(SW_S/D_S)$ auxiliary active power switch
$Q_1(SW_1/D_1)$ main active power switch
L_1 working coil inductance in primary side
L_2 spiral heater inductance in secondary side
M mutual inductance between working coil L_1 and internal spiral stainless steel heater circuit L_2
$k=\dfrac{M}{\sqrt{L_1 L_2}}$ electromagnetic coupling coefficient
R_2 skin effect related resistance of the spiral stainless steel heater
L_a effective input inductance in working coil side
R_a effective input resistance in working coil side
E DC source voltage
V_{Q1} voltage across main active power switch Q_1
i_{Q1} current through main active power switch Q_1

V_{Q2} voltage across auxiliary active power switch Q_s
i_{Q2} current through auxiliary active power switch Q_S
V_{L1} voltage across edge resonant reactor
i_{L1} current through edge resonant reactor
V_{C1} voltage across edge resonant lossless snubbing capacitor
i_{C1} current through edge resonant lossless snubbing capacitor
$\tau = \frac{L_2}{R_2}$ load time constant of heater spiral type
f switching frequency (inverter operating frequency
T inverter operating period
T_d dead time
T_{on_1}-T_d conduction time of SW_1 (Q_1)
T_{on_s}-T_d conduction time of SW_S (Q_S)
V_{g1} gate pulse to SW_1 (Q_1)
V_{gs} gate pulse to SW_S (Q_S)
$D = T_{on\_1}/T$ duty factor

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Visokofrekvencijski izmjenjivač s mekim sklapanjem i asimetričnim faktorom upravljanja za indukcijsko zagrijavanje tekućina. U članku je opisan način zagrijavanja vode u toplovodnom opskrbnom sustavu sa spiralno izvedenim grijačem u izmjenjivaču topline. Zagrijavanje vode u izmjenjivaču topline se postiže pomoću indukcijski grijanog grijača iz visokofrekventnog rezonantnog pretvarača. Primijenjeno je načelo komutacije sklopki pretvarača (IGBT) s minimalnim gubicima (meko sklapanje) s praćenjem prolaska napona kroz nulu. Na ovaj način realizirano grijanje osigurava optimalnu distribuciju topline i djelotvornu razmjenu topline u izmjenjivaču. Djelotvornost sustava je pokazana simulacijski i eksperimentalno.

Ključne riječi: meko sklapanje, visokofrekvencijski učinski pretvarači, ZVS pretvarači, rezonantni pretvarači

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