A Novel Induction Heating Type Super Heated Vapor Steamer using Dual Mode Phase Shifted PWM Soft Switching High Frequency Inverter

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Abstract

In this paper, a constant frequency phase shifting PWM controlled voltage source full bridge-type series load resonant high-frequency inverter using the IGBT power modules is presented for innovative consumer electromagnetic induction heating applications such as a hot water producer, steamer and super heated steamer. The full bridge arm side link passive quasi-resonant capacitor snubbers in parallel with the each power semiconductor device and high frequency AC load side linked active edge inductive snubber-assisted series load resonant tank soft switching inverter with a constant frequency phase shifted PWM control scheme is discussed and evaluated on the basis of the simulation and experimental results. It is proved from a practical point of view that the series load resonant and edge resonant hybrid high-frequency soft switching PWM inverter topology, what is called class DE type, including the variable-power variable-frequency (VPVF) regulation function can expand zero voltage soft switching commutation range even under low output power setting ranges, which is more suitable and acceptable for induction heated dual packs fluid heater developed newly for consumer power utilizations. Furthermore, even in the lower output power regulation mode of this high-frequency load resonant tank high frequency inverter circuit it is verified that this inverter can achieve ZVS with the aid of the single auxiliary inductor snubber.

Keywords-Series load resonant tank high-frequency inverter, Active auxiliary resonant AC load resonant inductor snubber, Lossless capacitive snubbers, Voltage-fed full brige inverter, Zero voltages soft switching, Induction heating, Dual packs fluid heater as a heat exchanger, Consumer power electronics

1. Introduction

In recent years, the electromagnetic induction eddy current based heat energy processing appliances and equipment in the industrial, automotive and consumer pipeline systems as well as cogeneration pipeline systems have attracted special interest which incorporate the voltage-fed series resonant type, the current-fed parallel resonant type, the voltage and current hybrid source-fed multi-resonant type, the edge-resonant type and auxiliary resonant high- frequency load resonant inverter circuit topologies using the latest IGBT power modules packages(CSTBTs) and intelligent power switch module(IPS) and intelligent power module(IPM). These high frequency resonant inverters have some advantageous points such as high efficiency, high reliability, high safety, cleanliness, compactness in volumetric physical size, lighter weight, rapid temperature control responses as well as stable temperature tracking and precise temperature controllability and multi-functionability. Under these technological backgrounds, some attractive electromagnetic induction eddy current based flow-through metal assembly package fluid-heating appliances using the voltage-fed edge resonant ZVS-PWM control type series load resonant tank high-frequency inverter circuit topologies operating at a constant frequency variable power regulation(CFVP) scheme has originally been proposed so far by the authors.

This paper presents a prototype of the voltage source type ZVS-PWM series load resonant high-frequency inverter with an active auxiliary edge resonant snubber in AC load side in addition to the auxiliary passive lossless capacitive snubbers in bridge arm side for the electromagnetic induction eddy current-based fluid heater, or dual packs fluid heater and dual packs steam heater as an induction heated heat exchanger in pipeline plants. Its operation principle and unique features of the newly-developed electromagnetic induction eddy current-based dual packs fluid heater which is composed of using the proposed voltage source soft switching series load resonant inverter using IGBT power modules are evaluated and discussed on the basis of simulation and experimental results from an application point of view.

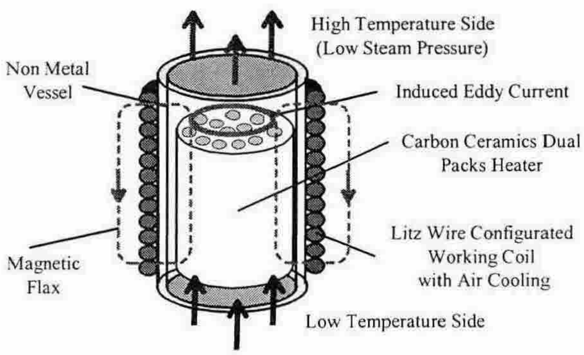


Fig. 1. System configuration of electromagnetic induction eddy current heater termed as dual packs fluid heater appliance developed newly.

2. Novel electromagnetic Induction Eddy Current-Based Dual Packs Fluid Heater

Figure 1 shows a schematic configuration of the new conceptual electromagnetic induction eddy current- based continuous fluid (liquids or gasses, vapor, powder) heater or induction heating (IH) dual packs fluid heater as a small scale IH boiler or IH heat exchanger. This flow-through IH dual packs heater as high efficiency IH heat exchanger is driven by the active voltage-clamped edge-resonant and passive capacitive snubber-assisted ZVS-PWM high-frequency inverter using IGBTs, which can operate with the phase-shifted PWM control strategy capable of extending the zero voltage soft switching commutation operating range.

The structure of specially-designed metallic laminated assembly to generate turbulence is shown in Fig.2. This new prototype of induction heating fluid heater, which is made of the electromagnetic induction heated type fluid-through thin metallic layer laminated assembly with many random spots and mechanically processed triangular wavelike channel slits in order to generate natural moving fluid turbulence in all kinds of consumer and industrial pipeline systems. This very thin metal layer package consists of thin conductive and non magnetic metal sheet heating body with a large amount of eddy current-based induction heating surface area, which is incorporated into the high-temperature proof ceramic vessel with non water-cooled working coil connected to the high-frequency inverter treated here.

In addition, Fig.3 illustrates the electromagnetic induction-based eddy current dual packs fluid heater using the high temperature carbon ceramic cylinder with many thin axial tubes. In this carbon ceramics developed as a new material, which is called semi-coke, the various types of powder ceramics are compounded, mixed and grounded on the basis of a special approach in cold isotonic pressing to cylindrical type of shapes, then burned and sintered more than 1500 degree centigrade. The new ceramics material produced newly are able to be made into several kinds of forms to suit best for the new application specific composite materials such as electromagnetic induction eddy-current based heater operating under a high temperature condition.

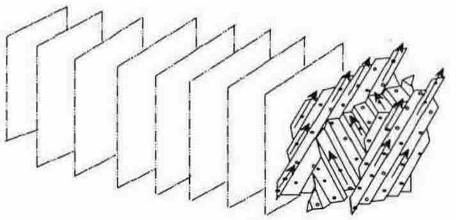


Fig.2. Specially-designed metallic laminated assembly dual packs heater to generate turbulence

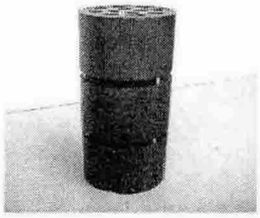


Fig. 3. Divided fluid-through carbon ceramics heating devices termed as induction heating dual packs fluid heater developed

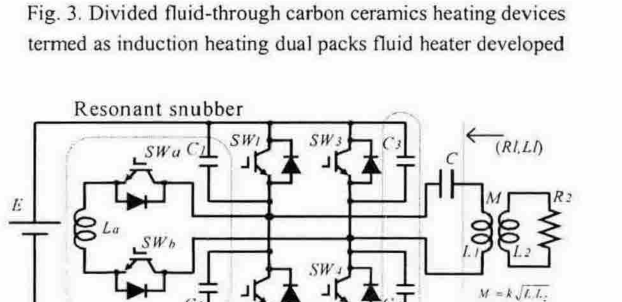


Fig. 4. Dual Mode Phase Shifted PWM Soft Switching High Frequency Inverter

The turbulence fluid flowing through this high frequency IH dual packs fluid heater appliance put tightly into the non metal vessel or chamber serves to convert electrical energy into efficient heat energy due to the electromagnetic induction eddy current based non contact fluid heating energy processing.

3. Dual Mode Phase Shifted PWM Soft Switching High Frequency Inverter

3.1 Soft Switching Commutation Operation

The control phase related power switch SW3 or SW4 in the voltage source full bridge type load resonant high frequency inverter in Fig.4 becomes the hard switching PWM operation

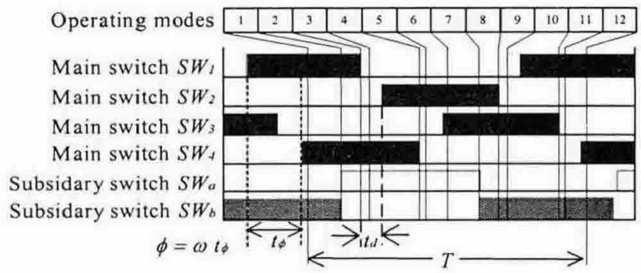


Fig. 5. Gate voltage pulse signal sequences and operating modes

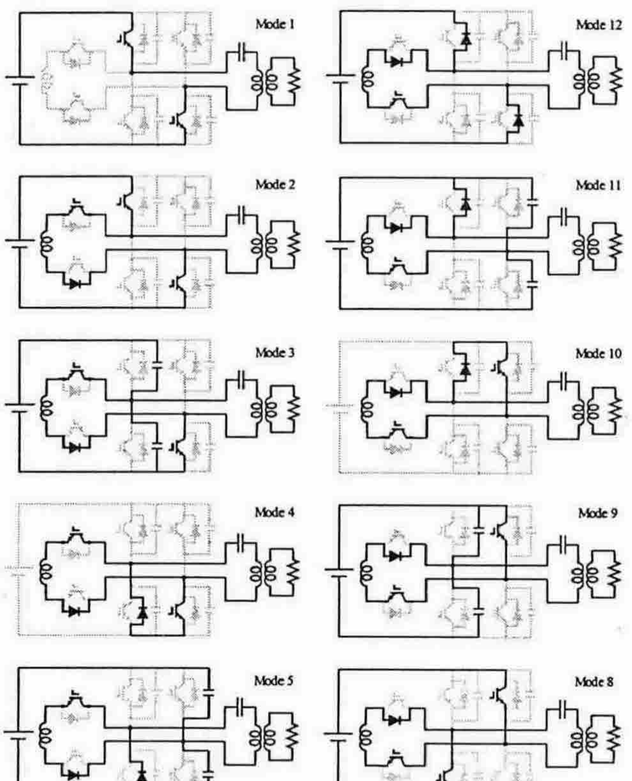


Fig. 6. Mode transitions and equivalent circuits of phase-shifted PWM series resonant soft switching inverter with auxiliary resonant AC link snubber

around phase difference angle $\phi = 90°$, for the voltage source full bridge type phase-shifted ZVS-PWM inverter with bridge arm linked lossless capacitive snubbers as shown in Fig.4. The bridge arm linked lossless snubber capacitor in parallel with the active power switches in the bridge legs by driving the bidirectinal switch in order to inject a certain value of initial edge resonant inductor current should be needed to discharge and charge the bridge leg associated lossless capacitors with the aid of the auxiliary edge resonant inductor, together with bridge arm link lossless capacitor snubbers. As a result, the complete zero voltage soft switching commutation operation of SW3 (SW4) in the right hand bridge leg can be achieved completely. The circuit design specifications and circuit parameters are indicated in Table 1.

3.2 Gate Pulse Control Implementation

The gate pulse pattern timing sequences of the edge resonant AC link inductor snubber and lossless capacitive snubber-assisted series load resonant high-frequency inverter circuit in Fig.4 are given in Fig.5. The auxiliary back to back reverse blocking IGBTs type bidirectional switch in parallel with the series compensated capacitor connected to the induction heating load is directly coupled to the actual induction heated inductive load circuit (Rl, Ll) without the high frequency matching transformer. By turning on the active auxiliary bidirectional switch in the auxiliary inductive snubber during the initial switching period, the auxiliary inductor current is sufficiently stored into the edge resonant inductor. This initial mode is to be utilized to discharge and charge for the lossless snubber capacitors for complete soft commutation.

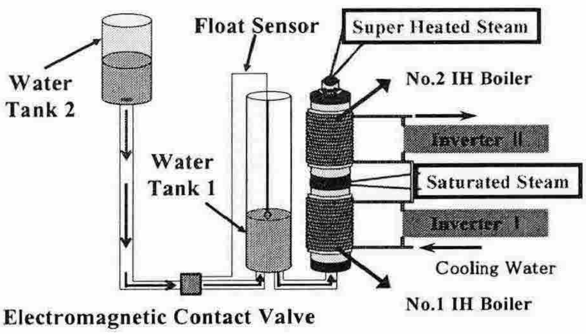


Fig. 7. Experimental setup of IH super heated steam generate system

Table 1. Design specifications and circuit parameters

Item	Symbol	Parameter constant
DC Source Voltage	E	140 V
Switching Frequency (Inverter Operating Frequency)	f	20 kHz
Capacitance of Power Factor Compensated Series Resonant Capacitor	C	2.9 μF
Inductance of Working Coil composed of Lits Wire	L_l	31.0 μH
Coupling Coefficient between L_1 and L_2	k	0.632
Load Time Constant	τ	8.1 μs
Capacitance of Lossless Snubber Capacitor	C_s	0.1 μF
Inductance of Auxiliary Resonant Inductor	L_a	22 μH
Resistance of Auxiliary Resonant Inductor	R_a	0Ω
Effective Resistance at Working Coil Side	R_l	0.78Ω
Effective Inductance at Working Coil Side	L_l	24.7μH

3.3 Operation Modes of Improved Inverter

The equivalent circuits for mode transitions of the phase-shifted ZVS-PWM high-frequency series load resonant inverter with auxiliary edge resonant snubber circuit are respectively shown in Fig.6. The phase-shifting PWM controlled high-frequency soft switching commutation series load resonant inverter circuit with the auxiliary resonant AC link inductor snubber includes 12 operating modes during this complete one output period when a single active auxiliary edge resonant AC link snubber circuit is operated in order to achieve the soft commutation. This auxiliary resonant AC link snubber is designed so as to operate in order to achieve soft commutation in the operating range less than the phase shift angle $\phi \cong 90°$.

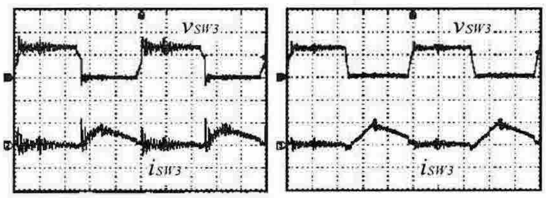
3.4 Schematic System of Super Heated Steamer

The schematic structure of super heated steam generator is shown Fig.7. In this paper, the experiment of setup implementation is carried out using this superheated steam generation system.

4. Experimental Results and Discussions

4.1 Comparative Measured Operating Waveforms

The typical measured operation waveforms of this improved high-frequency soft switching PWM inverter in case of phase difference angle $\phi = 120°$ are shown in Fig.8, respectively. Figure 8 represents the voltage and current waveforms in case of non auxiliary resonant AC link snubber circuit. In this case, it is noted that the hard switching operation for *SW3* in the right hand side bridge leg appears. Furthermore, this figure is depicted in case of using the AC load side configurated active auxiliary edge resonant snubber circuit (see Fig.4). In comparison with these figures, it is



(a)Without auxiliary circuit (b)Using auxiliary circuit

(10μs/div, 100V/div, 50A/div)

Fig. 8. For ϕ=120° phase difference, soft switching voltage and current waveforms of SW_3 in the control phase of bridge leg.

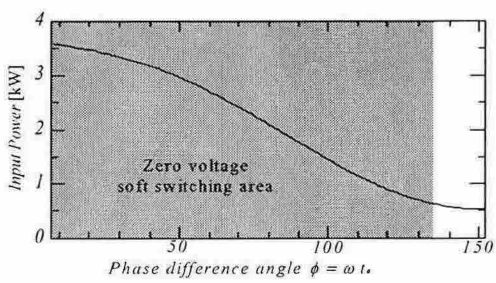


Fig. 9. Input power vs. phase difference angle characteristics.

$(\phi = \omega t_\phi, \omega = 2\pi/T = 2\pi f)$

proven that this improved phase shifted PWM high frequency inverter circuit with a single auxiliary resonant snubber treated here is more cost effective as its soft switching commutation can completely achieve even in large phase shifted PWM control ranges or low output power setting ranges.

4.2 High Frequency AC Power Regulation Characteristics

The output effective power regulation vs. the phase-shifted angle ϕ performance of this high-frequency series load resonant PWM inverter is depicted in Fig.9. The rated effective output power of this high frequency inverter is designed for about 4kW for IH-DPH to produce the high temperature vapour steam. The soft switching commutation range based on the dual mode phase-shifted PWM high frequency inverter (see Fig.4) becomes much larger than that of the previously developed high-frequency inverter circuit.

4.3 Power Conversion Efficiency Characteristics

Figure 10 illustrates the power conversion efficiency characteristics of the phase-shifted ZVS-PWM high-frequency series load resonant inverter with auxiliary edge resonant snubber circuit and non-auxiliary snubber circuit. In Fig. 10, the power conversion efficiency of the proposed inverter circuit with auxiliary resonant AC link snubber is higher than the previously developed high frequency inverter circuit without auxiliary resonant AC link snubber even in case of phase difference angle $\phi = 90°$ or more. However, the power conversion efficiency of developed inverter circuit relatively low become of additional power loss of the auxiliary resonant AC link even in case of phase difference angle $\phi = 90°$ or less. Therefore, this high frequency soft switching inverter circuit is more effective when in high power setting condition of this inverter, the auxiliary resonant AC link snubber circuit can not operate, and in low power setting condition, this inverter can operate with the aid of the auxiliary resonant AC link snubber circuit.

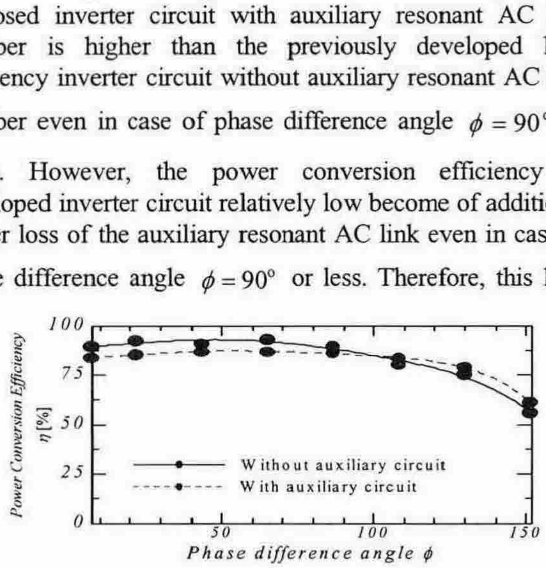


Fig. 10. Power conversion efficiency characteristics for different phase angle setting points. ($\phi = \omega t_\phi$, $\omega = 2\pi/T = 2\pi f$)

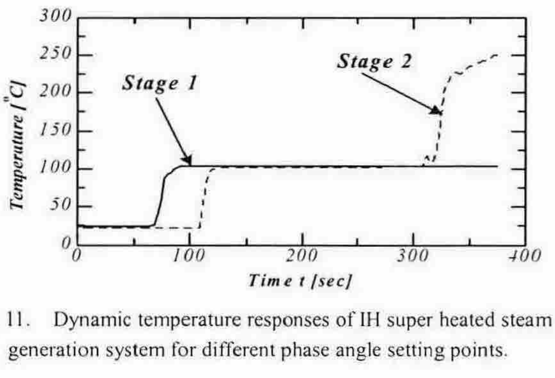


Fig. 11. Dynamic temperature responses of IH super heated steam generation system for different phase angle setting points.

4.4 Temperature Characteristics of Induction Heating Dual Packs Heater

Figure 11 illustrates the temperature characteristics of the induction heated hot water producer and steamer using the super heated steam generator. From this figure, the super heated steam of 250 degree temperatures generate after about 370 seconds from the IH system.

5. Conclusions

In this paper, the dual mode phase-shifted PWM full bridge series load resonant soft switching high-frequency inverter with bridge arm linked passive capacitor snubbers and/or edge resonant AC load side link inductive snubbers was originally developed by the authors for high efficiency induction heating (IH) type dual packs fluid heater (DPH) as the IH heat exchanger to work as steamer and super heated steamer. In the next place, the voltage source type phase-shifted PWM high-frequency series load resonant inverter which adds the AC load side active auxiliary inductor snubber and bridge arm linked auxiliary lossless capacitor snubber circuits were pointed out in order to realize the stable and wide soft switching commutation operated range not only under diversely specified high power setting ranges but also under lower power setting ranges. Its operating voltage/power regulation characteristics were illustrated and discussed herein.

This trially produced high-frequency series load resonant inverter setup controlled by the phase shifted PWM scheme for passive capacitive and/or active resonant snubbers was implemented by the open-loop control system for the induction heated steamer and super heated steamer. Moreover, the verification of the dual mode phase shifted PWM controlled high-frequency soft switching inverter equipment was confirmed and practical effectiveness of the edge resonant PWM high-frequency inverter-fed induction heating dual packs fluid heater used in a variety of new type boiler was considered and evaluated from a practical point of view.

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