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FACULTY OF ENGINEERING – SOHAG UNIVERSITY

Sohag Engineering Journal (SEJ), VOL. 2, NO. 1, MARCH 2022

Active Clamp Soft-Switched PWM High-Frequency Inverter for Induction Heated Hot Water Producer

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Abstract

This paper presents a new concept of stainless-steel eddy current-based electromagnetic induction screw type for heat exchanger or double pack heaters in hot water product, steam boiler and high heating evaporator, which is more suitable and acceptable to consumers of a new generation for energy applications. In addition, the active clamped edge-resonant high-frequency PWM inverter using trench-gate IGBTs power module can operate according to the zero-voltage soft-switching principle with PWM and has been developed and proven for high-efficiency hot water heating boiler and product in consumer power applications. The power device for consumer induction heater using active-clamp soft-switched PWM high-frequency inverter is evaluated and discussed based on simulation through PSIM and experimental results. To extend the operating ranges of zero-voltage soft-switching under a low-power setting as well as improve efficiency, a high-frequency pulse density modulation strategy for a high-frequency soft-switched inverter is demonstrated. The practical effectiveness of induction heating power supply has been greatly proven from the point of view of induction heating application.

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Keywords: High-Frequency Inverter, Edge-Resonant Soft-Switching PWM, Duty Cycle Control, Induction Heated Steamer Dual Packs Heater, Consumer Power Electronics.

1. INTRODUCTION

The main source of heating, cooling, and electrical power generation applications is natural gas [1, 2], a fossil fuel, which in turn is exacerbating the looming global warming. Therefore, new-age residential induction heaters pave the way for the replacement of traditional electric and gas heating technologies. Induction Heating (IH) systems have inherent advantages, such as higher conversion efficiency, being cleaner, and having less time to acquire heat [3]. On the other hand, IH incurs more efficient clean energy disposal [4, 5]. Compared with traditional heating techniques such as resistive heating, flame heating, or arc furnaces, IH is more suitable for industrial applications because it is more effective and efficient [6-9]. More importantly, methodologies for an inherently safe pregnancy in IH are very favorable for many medical applications [10-14]. The portability and plug-and-play aspects of IH-supported devices mean that they are in high demand concerning home applications [15-17].

In recent years, electromagnetic induction eddy current-based heat energy processing and utilization systems using a variety of high-frequency high-power inverters have attracted special interest from the viewpoints of high efficiency, high reliability, safety, cleanliness, compactness in volumetric size, light in weight, rapid temperature response for particular high-power applications in industry automotive and consumer fields [18-20]. The electromagnetic IH is concerned with non-contact, high efficiency, and clean electric heating method due to the energy conversion heated device by induction eddy current based on Faraday's law of electromagnetic induction principle in addition to Joule's heating principle [21-23]. Induction heating technology has a wide range of usage areas such as melting, annealing, welding, tight passing, hardening, forming, cooking and plasma physics [24, 25].

There are various induction water heaters developed recently. But those heaters were designed for water heating. Also, academic studies have been focused on water heating. Thus, an induction water heater system seems to be a useful innovation [26]. The high-frequency inverters of induction heating applications can supply high-frequency power to IH load, which consists of working coil and eddy current-based heating materials.

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Some high-frequency inverters operating overpower frequency ranges from 20 kHz to several MHz need to be cost-effective, high efficiency and have high power density [19, 20, 27, 28]. There are various high-frequency inverter circuit topologies, such as full-bridge, half-bridge, single-ended push-pull, center tap push-pull and boost half-bridge. Of these, the voltage source type ZCS (zero current switching) [29], ZVS (zero voltage switching), SEPP (Single-Ended Push-Pull) resonant and the quasi-resonant hybrid high-frequency inverter has unique features, such as simple configuration, high efficiency, and wide soft commutation range [27-34]. The proposed inverter is configured by IGBTs and evaluated by simulation diagrams [19, 35].

This paper presents a new conceptual energy-saving type electromagnetic eddy current-based induction heater, which is more suitable and acceptable for induction heated hot water producer, boiler and steamer. On the other hand, active voltage-clamped type zero voltage soft switching PWM high-frequency inverter connected to utility AC 200V-RMS for consumer power applications is developed and demonstrated from a practical point of view [36-38]. In this paper, a new style compact induction heated hot water producer and steamer using soft-switching PWM high-frequency inverter is also discussed and evaluated from the experimental and simulation points of view.

This paper is organized as follows: In Section 2, induction eddy current-based heated hot water producer. In Section 3, new conceptual induction heater. In Section 4, active clamping quasi-resonant ZVS PWM high-frequency inverter. In Section 5, experimental results, and discussions and finally, the conclusion is in Section 6.

2. INDUCTION EDDY CURRENT-BASED HEATED HOT WATER PRODUCER

2.1. Induction Heated Load Technology and Circuit Modeling

A prototype of the induction eddy current-based heated hot water producer and steamer is schematically illustrated in Fig. 1. This energy conversion device based on an electromagnetic induction-heated type heat exchanger composed of the dual pack's heater is made of a new conceptual induction heater which is built and tested by spiral stainless-steel assembly, working coil (Litz wire), nonmetal heating vessel made of the polycarbonate, high-frequency soft-switching inverter using IGBTs and diode rectifying converter.

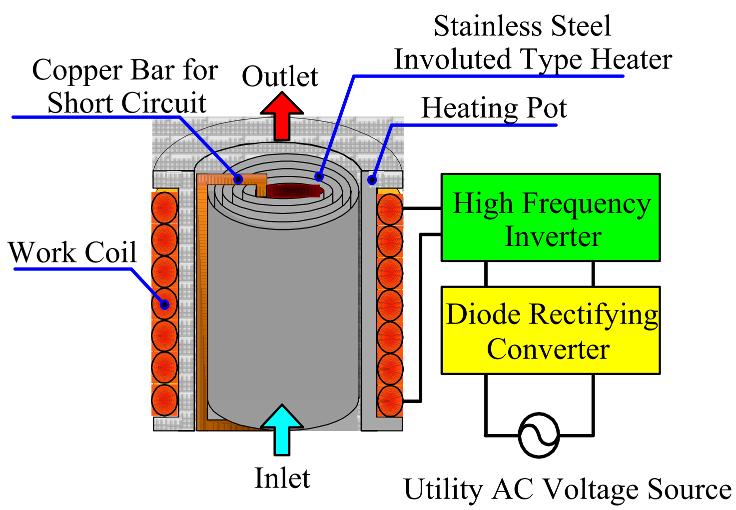


Fig. 1. Induction heating water producer.

An electromagnetic induction heater for compact hot water producer and steamer using high-frequency inverter driven by the diode rectifier with a non-smoothing filter has to be designed for the following requirements: (a) uniform temperature distribution, (b) wide eddy current heating surface, (c) no erosion, (d) no thermal deformation for power injection or rejection, (e) small heat capacity. In this paper, a new conceptual induction heater made of non-magnetic stainless steel SUS316 plate is demonstrated that has a spiral assembly with a short circuit called copper bar end ring for quick temperature response in specified temperature setting. It is composed of the spiral assembly and its outside edge point is connected to the inside edge point by connecting the low resistance copper bar between two edge points. In this technique, it is possible to achieve a uniform temperature distribution of an electromagnetic induction eddy current-based joule's induction heated type heat exchanger.

In general, it is difficult to form the spiral structure toward its center. In the case of rolling toward its center, effective increment of the heating surface could not expect actually. But if no obstacle is inserted in the center of the spiral plate structure, the heat exchange efficiency of this induction heater decreases because a large majority of the heated liquid flows through the center. To improve reduced heat exchange efficiency, the cylindrical polycarbonate material is inserted toward the center of this vessel. The geometric size and shape of this induction heater are designed as illustrated in Fig. 2.

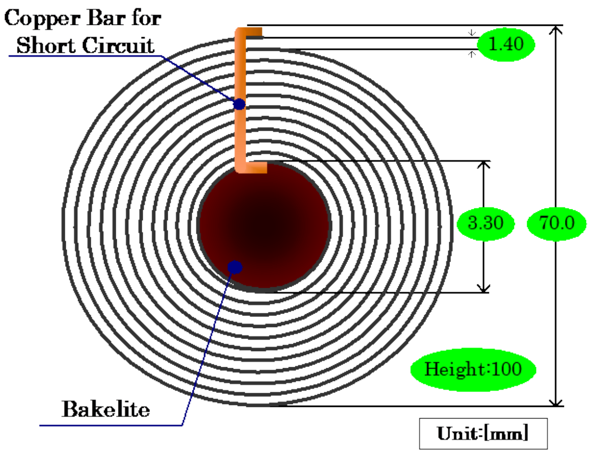


Fig. 2. Top view appearance of electromagnetic induction eddy current-based heater.

3. ACTIVE CLAMPING QUASI-RESONANT ZVS PWM HIGH-FREQUENCY INVERTER

3.1. Circuit Description

Fig. 3 shows an active clamp high-frequency inverter circuit topology that can operate under a condition of zero voltage soft switching (ZVS) and constant frequency duty factor regulated mode asymmetrical pulse width modulation (PWM) control strategy for power regulation. This active voltage clamps high-frequency inverter using IGBTs, which has some advantageous points such as wide soft-switching operation range, low peak voltage stress for power switching devices and high efficiency, which is developed and implemented for electromagnetic induction eddy current-based heated hot water producer and steamer and boiler. Introducing the voltage-clamped capacitor (C_S) in series with an auxiliary active power switch, this high-frequency inverter can effectively clamp an excessive peak voltage applied to the main active power switch (SW_1). Besides introducing an auxiliary switch (SW_S), this high-frequency inverter can operate under a constant frequency asymmetrical pulse width modulation (PWM) control strategy. In Fig. 3 this induction heated hot water producer driven by this inverter is represented as the transformer type equivalent circuit model.

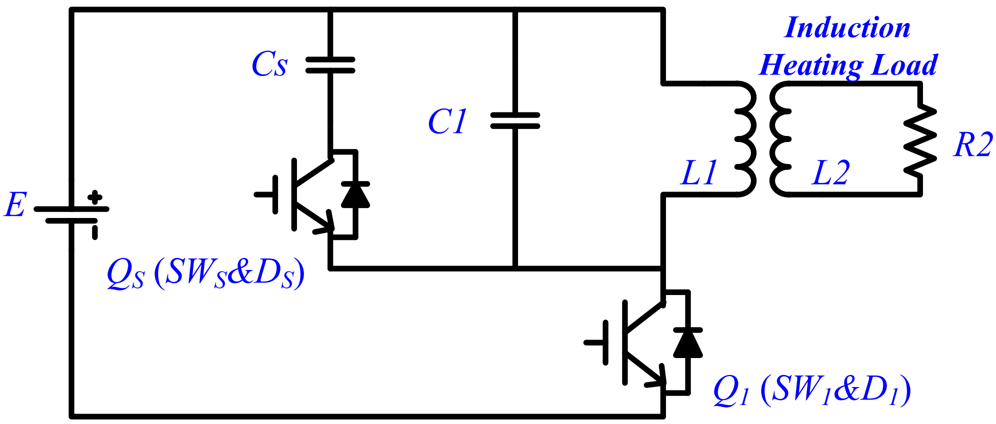


Fig. 3. Active voltage-clamped edge-resonant high-frequency inverter.

3.2. Gate Pulse Control Implementation

Fig. 4 illustrates timing asymmetrical PWM pulse sequences for the high-frequency inverter shown in Fig. 3. These voltages pulses are supplied to the power semiconductor switching block; Q_1 (SW_1&D_1) and Q_S (SW_S&D_S). Duty Factor defined as D=ton/T serves as a control variable for the continuous power regulation for this edge-resonant soft-switching PWM inverter using IGBTs. Duty Factor is designed as a ratio of the conduction time including a dead time of the main active power switches during one period.

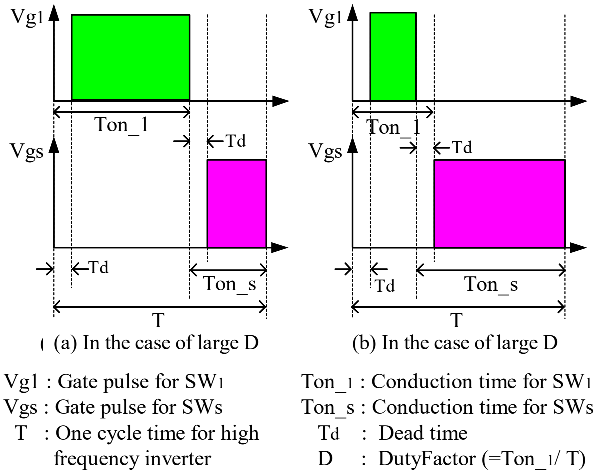


Fig. 4. Asymmetrical PWM gate voltage pulse signal sequences.

When the full power is delivered to the load, the conduction time of the main active power switch during one cycle is lengthened as indicated in Fig. 4 (a). On the other hand, when full power is not required for load, the conduction interval is shortened as indicated in Fig. 4 (b).

4. SIMULATION RESULTS

4.1. PWM Control Technique

The most commonly used pulses with modulation [41] are applied to the IH system to control the output power. For variable loads, the power semiconductor switches enter into the hard-switching mode, which increases the switching stresses. To overcome this problem, dual-loop controls were developed using a phase-locked loop (PLL) and a PI controller [39, 40, 41, 42]. The PLL, the first loop control, is used to track the resonant frequency to maintain the soft switching in the inverter and the outer loop controls the output power. The general block diagram of the PLL-assisted PI control is shown in Fig. 5. The dual-loop controls make the system more complex and slower down the dynamic response. This problem required a solution to develop a suitable modulation technique that would be good for both the soft-switching action and the power control. The flowchart of the PLL-assisted PWM control technique is shown in Fig. 6.

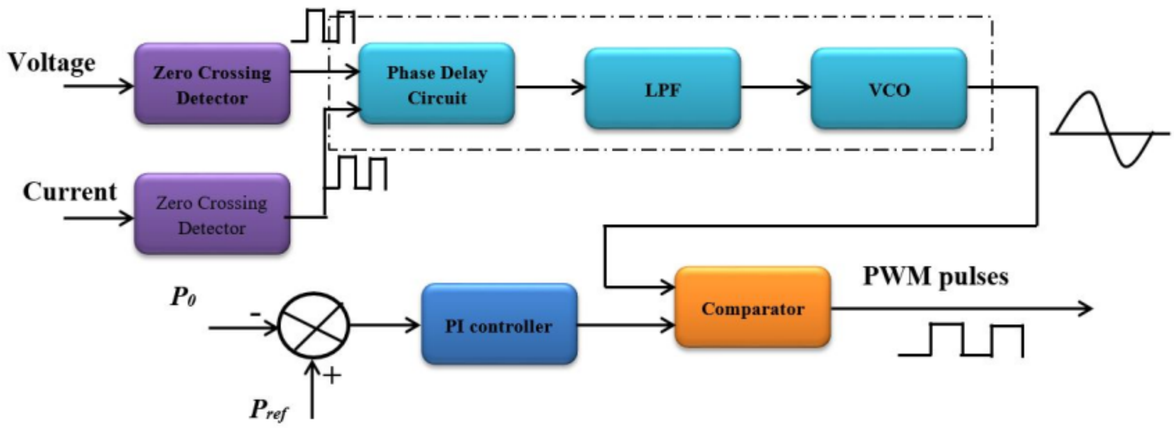


Fig. 5. A general block diagram of PLL-assisted PI control.

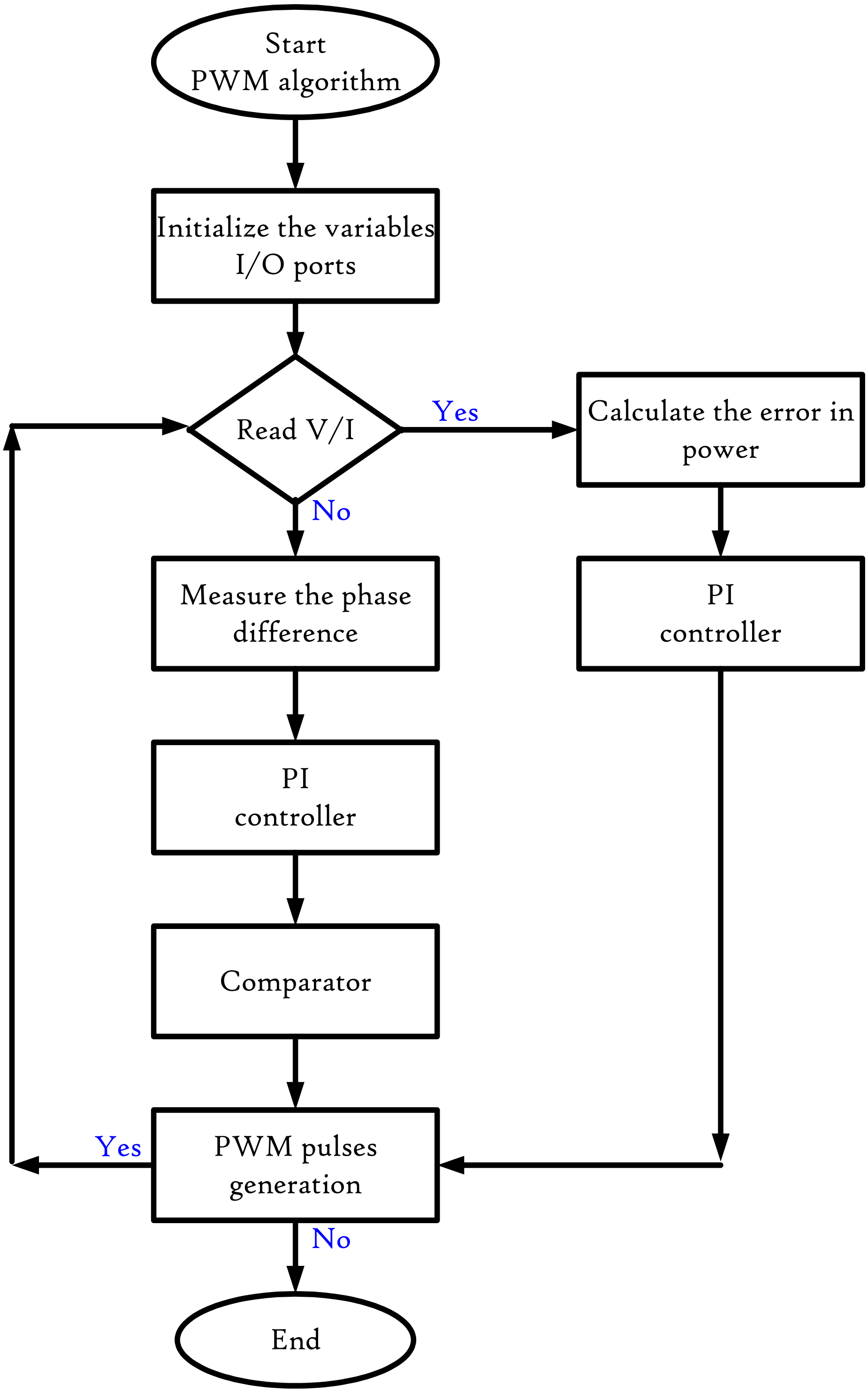


Fig. 6. Flow chart of PLL-assisted PWM control technique.

4.2. Switching Voltage and Current Waveforms

Fig. 7 shows 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 Fig. 7 both the main active power switch and the auxiliary active power switch can achieve soft switching completely. Besides, this active voltage clamp high-frequency load resonant inverter can suppress an excessive peak voltage applied to the main active power switch for Modes 3 and 4. This high-frequency inverter in steady-state includes periodically repeated operation with 6 modes. Figure 8(a) shows the input AC voltage at 50 Hz and output voltage at 20 kHz. At the same time Fig. 8(b) shows the output voltage and current of the inverter.

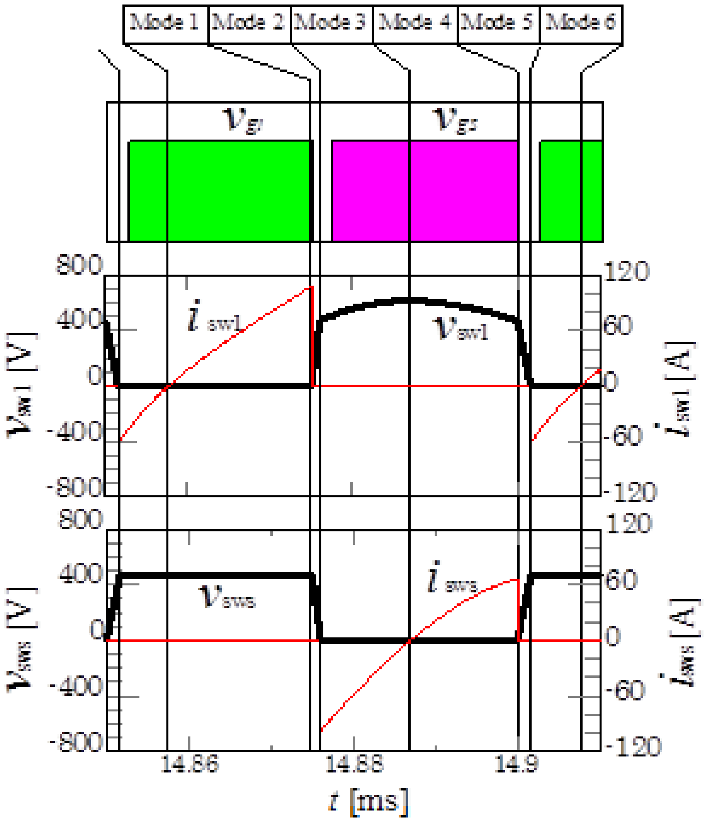
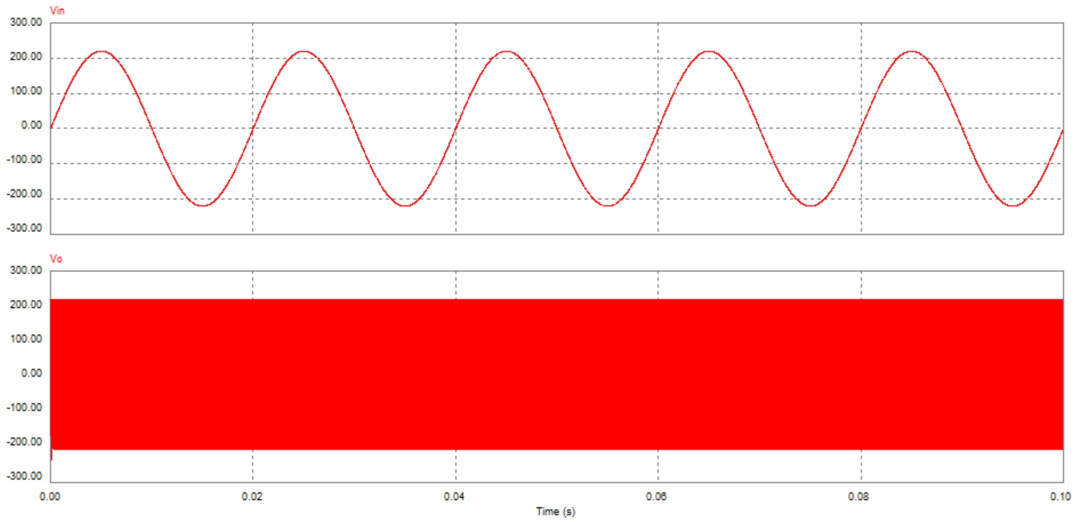
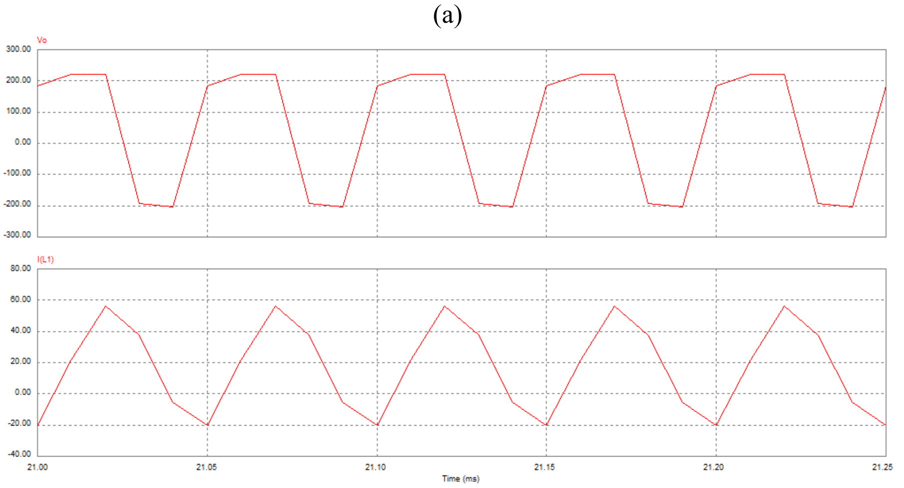


Fig. 7. Steady state switching waveforms.



(a)



(b)

Fig. 8. (a) Input 50 Hz AC voltage and output voltage at 20 kHz, (b) Output voltage and current of the inverter, (Simulation Results).

Fig. 9 represents duty factor versus input power regulation characteristics and duty factor vs. peak voltage characteristics for a new prototype of induction heating energy conversion device under a constant frequency asymmetrical PWM control strategy. Observing this Fig. 9 it is proved that the inverter output power can be continuously adjusted in the accordance with duty factor or duty cycle *D* as a control variable.

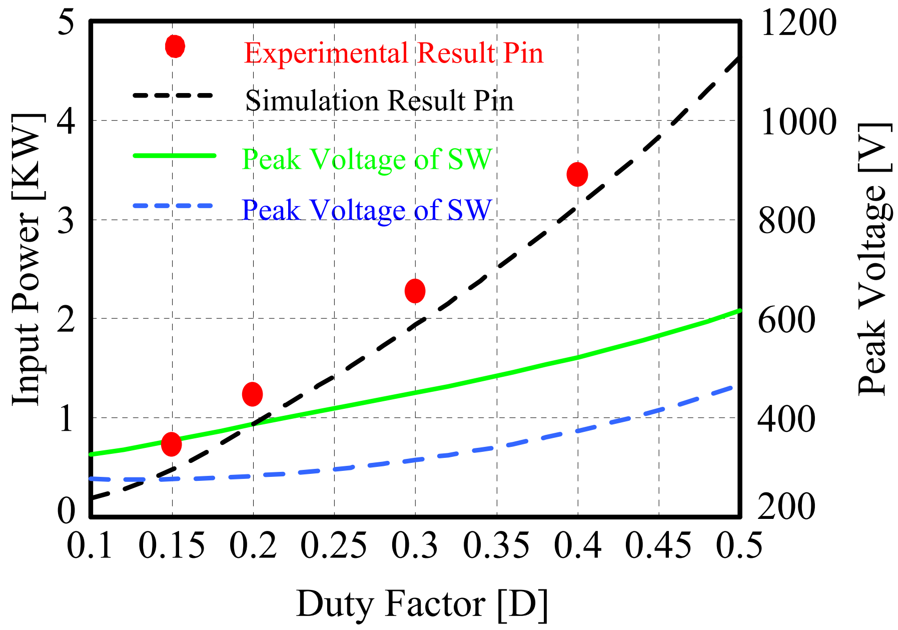


Fig. 9. Duty factor vs. input power and peak voltage characteristics.

5. EXPERIMENTAL RESULTS AND DISCUSSIONS

5.1. Design of Experimentally produced Hot Water Producer

An experimental prototype was developed to supply an induction heating load of 100W. Commercially available 50 Hz AC was rectified using four 1N4007 diodes and two IRF840 MOSFETs used to convert DC to HFAC. Hardware layout of IH power supply system is shown in Fig. 10. A PIC16F877A microcontroller is used to validate the used topology. Table 1 indicates the practical design specifications and circuit parameters of the feasible electromagnetic induction-based heated hot water producer and steamer using edge-resonant ZVS-PWM soft-switching high-frequency load resonant inverter using the IGBT modules.

Fig. 10. Test setup of IH power supply system.

TABLE 1. DESIGN SPECIFICATION AND CIRCUIT PARAMETERS

Item	Symbol	Value
DC Source Voltage	E	200 V
Switching Frequency	f_{sw}	20 kHz
Edge-Resonant lossless 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

5.2. Temperature Characteristics

Fig. 11 illustrates the temperature response characteristics of the induction heated hot water producer and steamer composed of specially designed spiral type induction heater using active voltage clamp high-frequency inverter which is built and tested in the experiment. It is noted that this inverter type compact induction heated hot water producer and steamer using new conceptual electromagnetic induction eddy current-based heater in pipeline systems can heat rapidly than conventional gas combustion type or sheathed wired heating type.

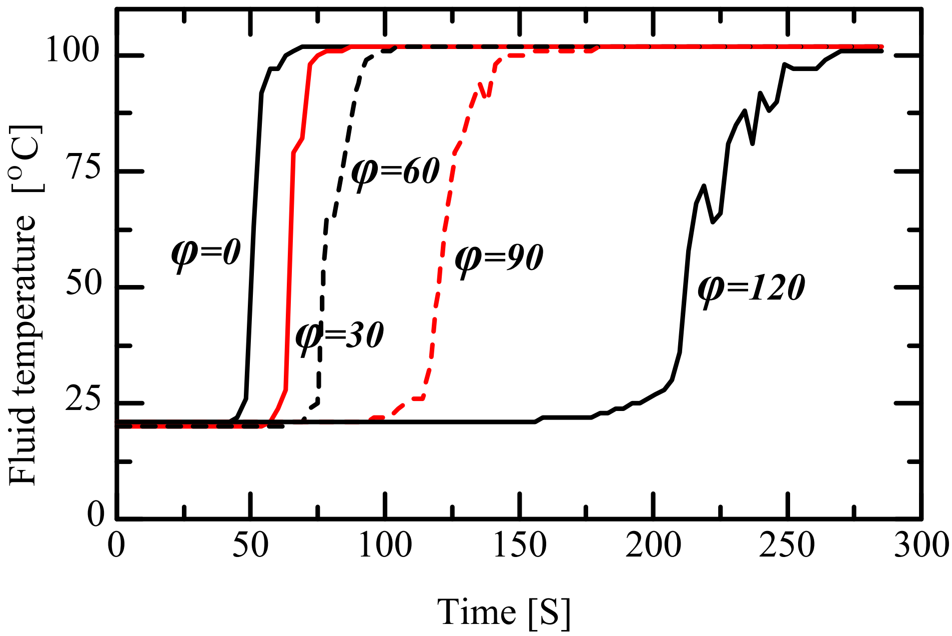


Fig. 11. Fluid temperature response characteristics of IH hot water producer and steamer.

5.3. Observed Waveforms

Fig. 12 illustrates 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 specified condition of duty cycle $D = 0.5$. Besides, it is proved that this active clamp edge-resonant ZVS-PWM high-frequency inverter using IGBTs can completely work under the operating principle of zero voltage soft switching commutation for a wide duty factor control scheme. This active clamped edge-resonant high-frequency inverter can limit an excessive peak voltage applied to the main active power switch. Accordingly, the conduction power losses as well as voltage and current peak or dynamic derivative stresses of switching power semiconductor devices; IGBTs can be considerably reduced in this high-frequency inverter circuit topology.

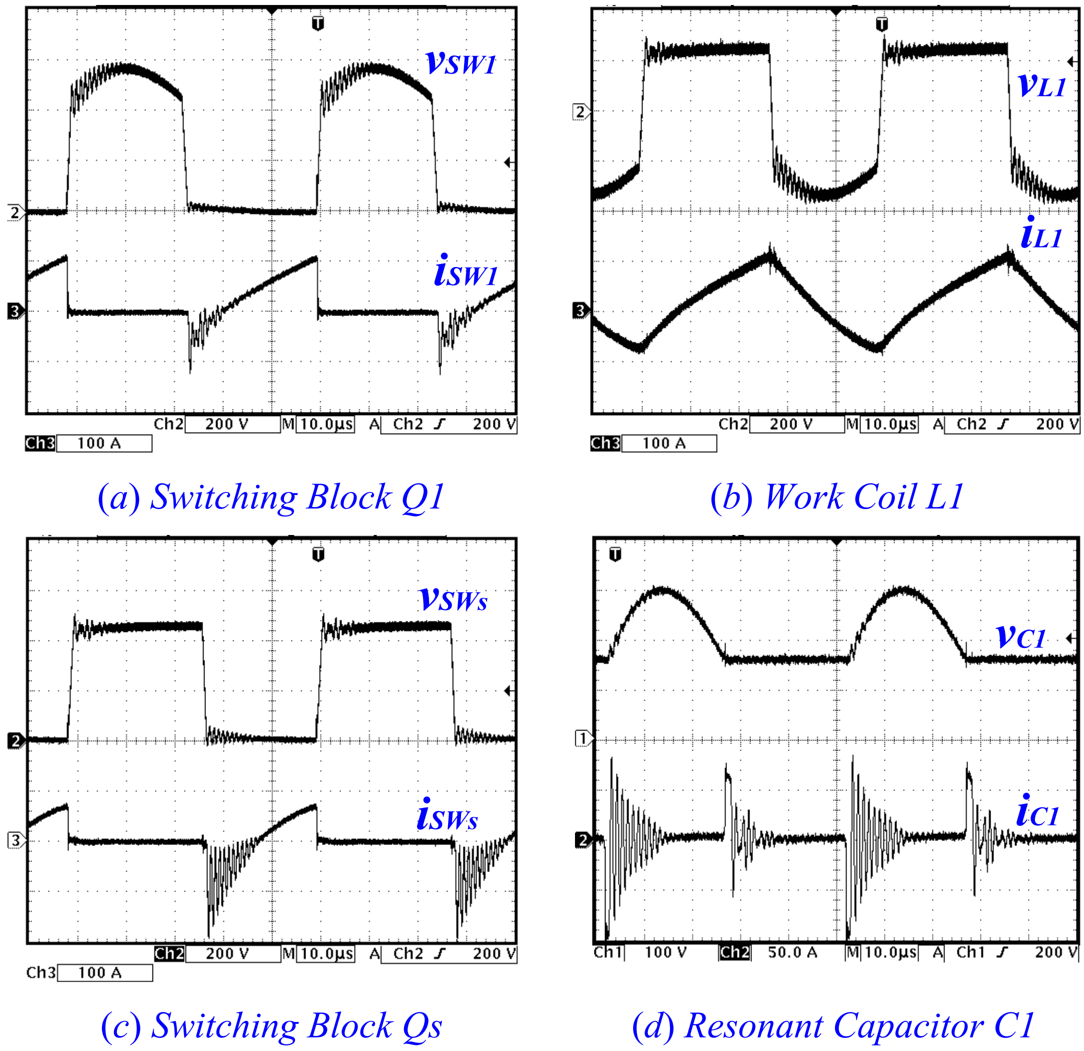


Fig. 12. Experimental voltage and current waveforms (Duty Factor $D = 0.5$).

6. CONCLUSION

In this paper, the novel prototype of electromagnetic induction eddy current-based hot water producer and steamer using active clamp high-frequency quasi-resonant inverter has been successfully proposed and demonstrated from a practical point of view. In addition, an active voltage-clamped edge-resonant ZVS-PWM high-frequency load resonant inverter using the latest trench IGBT module, which can efficiently operate under a zero-voltage soft commutation based on asymmetrical PWM (Duty Ratio Control) strategy. These induction heated appliances for pipeline fluid heating using active voltage clamp edge-resonant high-frequency inverter could be more cost-effective than the conventional gas combustion heating type or sheathed wired heating type. In the future, the power loss analysis of this soft-switching high-frequency inverter using the CSTBTs in new generation should be done for consumer induction-heated hot water producer and boiler, and steamer as well as super-heated steamer in pipeline systems.

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