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Three-Phase High Frequency AC Conversion Circuit with Dual Mode PWM/PDM Control Strategy for High Power IH Applications

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***Abstract*—**This paper presents a novel three-phase utility frequency to high frequency soft switching power conversion circuit with dual mode pulse width modulation and pulse density modulation for high power induction heating applications as melting of steel and non ferrous metals, annealing of metals, surface hardening of steel and cast iron work pieces and hot water producers, steamers and super heated steamers. This high frequency power conversion circuit can operate from three-phase systems to produce high current for high power induction heating applications under the principles of ZVS and it can regulate its ac output power from the rated value to a low power level. A dual mode modulation control scheme based on high frequency PWM in synchronization with the utility frequency positive and negative half cycles for the proposed high frequency conversion circuit and utility frequency pulse density modulation is produced to extend its soft switching operating range for wide ac output power regulation. A dual packs heat exchanger assembly is designed to be used in consumer and industrial fluid pipeline systems and it is proved to be suitable for the hot water, steam and super heated steam producers. Experiment and simulation results are given in this paper to verify the operation principles of the proposed ac conversion circuit and to evaluate its power regulation and conversion efficiency. Also, the paper presents a mutual coupling model of the induction heating load instead of equivalent transformer circuit model.

***Keywords*—**Induction heating, three-phase, conversion circuit, pulse width modulation, pulse density modulation, high frequency, soft switching.

I. Introduction

INDUCTION heating (IH) is one of a wide range of electrical heat used in industry and household today. The main applications of the process are in the food processing and cooking appliances, hot water, steam and super heated steam producers, steel and metal working industries. Clean and fast heat being supplied to the heated work piece meets the considerably increased requirements with regard to environmental protection. The surroundings are not exposed to any thermal and atmospheric pollution. The particular advantage of this process is to produce the heat inside the work piece without the need for any external heat source [1]-[5].

According to the physical law of induction an alternating magnetic field is generated around each electrical conductor through which an alternating current is flowing. By considerably increasing these magnetic fields, metals brought into close proximity will be heated by eddy currents produced within the metal. Heating by induction makes use of the capability of the magnetic field to transmit energy without direct contact. This means heating is not done by contact transmission such as known in resistance heating in light bulbs, heating plates or electrical furnaces where the direct current flow causes resistance wires to glow.

A basic problem of induction heating is to create a sufficiently intense electro-magnetic field and to position the component to be heated within the center of the field in such a way as to obtain optimum transmission of energy from the electrical conductor to the work piece. Normally this is achieved by forming the electrical conductor also referred to as inductor or coil with one or more turns. The work piece is positioned in the centre of the coil, thus concentrating the magnetic field onto the component. The field will then force the electrical current to flow within the work piece. According to the law of transformation, the strength of the current flow in the component is equal to that in the coil. To create a sufficiently strong magnetic field, the current flow in the coil must be very high (1000–10A). Another method of creating a strong alternating magnetic field is to increase the frequency of the current. Depending upon the application, induction heating equipment can be roughly classified into low frequency and high frequency (20kHz or more). These high frequencies, which are not available from the normal mains electrical supply, are obtained by means of high frequency conversion circuits [6]-[7].

It may be asked why such a large frequency range is necessary and why not all induction heating processes cannot be carried out at the same frequency. This is due to a physical reason as well, i.e. the so called skin effect. The electrical current flows into the outer skin of the work piece only, this means the center of the work piece remains theoretically cold. The thickness of the layer in which the current flows in turn is dependent on the frequency. At low frequencies, the layer is thick, i.e. the work piece is penetrated by the current almost to the centre, and consequently heated through. At very high frequencies, the current flows at the surface only and the penetration depth is in the range of 0 to 1 mm. This effect is made using the frequency appropriate for the application [8].

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Fig. 1 shows the relation between the penetration depth and the working temperature as a function of the working frequency in steel.

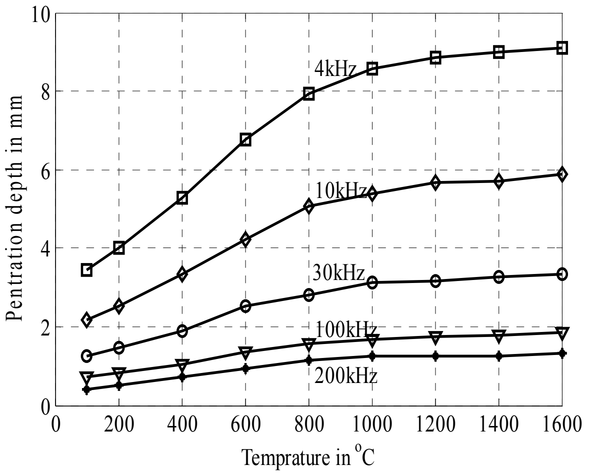


Fig. 1 Penetration depths for different frequencies in steel

The most common applications utilizing induction heating technology are:

- Melting of steel and non ferrous metals at temperatures up to 1500 °C.
- Heating for forging to temperatures up to 1250 °C.
- Annealing and normalizing of metals after cold forming using temperatures in the range of 750 – 950 °C.
- Surface hardening of steel and cast iron work pieces at temperatures from 850 – 930 °C (tempering 200-300 °C) and soft and hard soldering at temperatures up to 1100 °C, moreover, special applications such as heating for sticking, sintering.
- Hot water, steam and super heated steam producers.
- Food processing and cooking appliances.

While for melting, forging and annealing mostly medium frequency is used as energy source, for hardening and soldering applications it depends on the requirements whether high or medium frequency can or is to be used.

There is a wide range of IH conversion circuits available in the market for IH applications, with power levels ranging from hundreds of watts to several kilowatts. For typical applications, the typical power level is 1kW. However, the market for IH applications is growing quickly, as is the power level required for such applications. A typical block diagram of a conventional IH power conversion circuit supplied by an ac power source, which can be either a single- or three-phase bus, consists of three stages of power conversion. The power is first processed by a rectifier circuit to obtain a dc voltage represented by single- or three-phase diode rectifier. Each IH power conversion consists of a smoothing stage and a high frequency inversion stage to provide a high frequency power to the IH applications. Besides supplying power to the IH load, the power conversion, for instance, is also used to regulate its output power. However, the harmonic distortion inherently produced in the commercial ac input utility side due to the rectified dc smoothing voltage link with electrolytic smoothing capacitor. In addition, the significant problems on power conversion efficiency, volumetric physical size as reliability and life of the electrolytic capacitor dc link power stage have actually appeared by using the electrolytic capacitor bank or assembly for the dc voltage smoothing [6]-[8].

For the next generation of high-power IH applications, not only the overall performance but also the cost of the entire system will be important issues to be considered during the design process. The power conversion circuit for IH applications must achieve high efficiency, low harmonic distortion, high efficiency, high power density, high reliability and low electromagnetic interference (EMI) noise. To reduce the cost of the IH appliances, the power conversion circuit must be inexpensive, while still complying with standards for harmonic distortion.

One of the conventional practices, commonly used, is the use of a one-stage approach based upon utility frequency to high frequency conversion circuit by eliminating the rectification and smoothing stages, whereas meeting harmonic current standards such as the IEC 61000-3-2. In this way, the intermediate smoothing bus capacitor can be eliminated, as discussed in previous papers [9]-[11].

This paper presents a possible approach for reducing the cost of the IH conversion circuit by connecting the three outputs of the single-phase modules of previously developed utility frequency to high frequency conversion circuits, which is suitable for high power IH applications operating from three-phase systems as heat treatments of metals or super heated steam producers. It is a one-stage high-frequency conversion circuit, composed of three single-phase modules of previously developed utility frequency to high frequency power converter [11]. Soft switching operation, high current and high power conversion efficiency are the main features of the proposed high frequency conversion circuit. In addition, paralleling decreases the power dissipation and current per module because each module is required to handle less power in the system, which helps simplify thermal design [12].

II. Modeling of IH Load

A. Transformer Circuit Model

The equivalent transformer circuit model of the IH load can be represented as shown in Fig. 2, where L_1 is the self-inductance of the IH work coil and defined by the high frequency magnetic flux caused by the inverter current, L_2 and M are the secondary side and the mutual inductances of the transformer, respectively. R_2 is the resistance of the IH load which its value depends on the operating frequency. With neglecting the internal resistance of the IH work coil, the following circuit equations can be derived as follow:

$$\begin{cases} j\omega L_1 I_{L1} + j\omega M I_{L2} = V_{L1} \\ j\omega M I_{L1} + (j\omega L_2 + R_2) I_{L2} = 0 \end{cases} \tag{1}$$

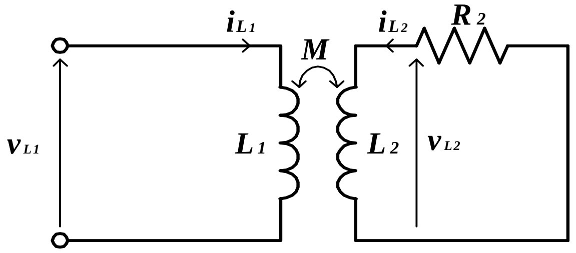


Fig. 2 Transformer model of induction heating load

Observing the above equation and rearranging, the following equation can be obtained,

$$\frac{V_{L1}}{I_{L1}} = \frac{\omega^2 M^2 R_2}{R_2^{\,2} + \omega^2 L_2^{\,2}} + j\omega \frac{L_1 R_2^{\,2} + \omega^2 L_2 (L_1 L_2 - M^2)}{R_2^{\,2} + \omega^2 L_2^{\,2}} \tag{2}$$

The real and imaginary parts of the above equation can be represented by R_a and $j\omega L_a$, as follows:

$$\begin{cases} R_a = \dfrac{\omega^2 M^2 R_2}{R_2^{\,2} + \omega^2 L_2^{\,2}} \\ L_a = L_1 - \dfrac{\omega^2 L_2 M^2}{R_2^{\,2} + \omega^2 L_2^{\,2}} \end{cases} \tag{3}$$

As a result, the equivalent electrical model of the IH load as shown in Fig. 2 can be represented by R_a and L_a which can be measured experimentally.

B. *Mutual Coupling Model*

The transformer electromagnetic mutual coupling coefficient k and time constant of the IH load τ can be defined as;

$$\begin{cases} k = \dfrac{M}{\sqrt{L_1 L_2}} \\ \tau = \dfrac{L_2}{R_2} \end{cases} \tag{4}$$

For a time constant τ of the IH load, the circuit behavior of the IH load is the same for any value of L_2 and R_2. Therefore, it is better to represent the IH load by using the parameters L_1, k and τ defined in (4) instead of using the circuit parameters of the equivalent transformer circuit model of the IH load as depicted in Fig. 2, where L_1 can be easily measured instead of L_2, M and R_2 which cannot be easily measured. If k and τ defined by (4) are represented by the measurable parameters R_a, L_a and L_1, the operation of the inverter circuit with the IH load analysis will become much more simple.

The following equation can be defined from (3) as,

$$M^2 = \frac{R_a (R_2^{\,2} + \omega^2 L_2^{\,2})}{\omega^2 R_2} \tag{5}$$

From (3) and (5), the following equation can be written,

$$R_2 (L_1 - L_a) = R_a L_2 \tag{6}$$

where $\tau = L_2 / R_2$, so the time constant τ of the IH load can be redefined as;

$$\tau = \frac{L_1 - L_a}{R_a} \tag{7}$$

Therefore, the time constant τ can be estimated by using the measurable parameters R_a, L_a and L_1.

The resistance R_2 can be obtained by using (6) as follow:

$$R_2 = \frac{R_a L_2}{L_1 - L_a} \tag{8}$$

By substituting R_2 in (8) to (3) and multiplying the resultant equation by $1/L_1$, the following equation is derived;

$$\frac{M^2}{L_1 L_2} = \frac{R_a^{\,2} + \omega^2 (L_1 - L_a)^2}{\omega^2 L_1 (L_1 - L_a)} \tag{9}$$

The transformer electromagnetic mutual coupling coefficient τ is represented by the measurable circuit parameters R_a, L_a and L_1 as,

$$k = \sqrt{\frac{R_a^{\,2} + \omega^2 (L_1 - L_a)^2}{\omega^2 L_1 (L_1 - L_a)}} \tag{10}$$

The k and τ are calculated by the experimentally measurable parameters R_a, L_a and L_1 as described in (7) and (10) and a function of the operating frequency $\omega = 2\pi f$. In the experimental work, the following parameters have been measured by using the high frequency linear power amplifier (NF Circuit Design Block Co. Ltd, type 4520) at the frequency 20kHz as $L_1 = 90\mu H$; $L_a = 78\mu H$; $R_a = 1.3\Omega$. The circuit parameters of IH load is considered constant as the output frequency of the conversion circuit is kept constant in spite of output power regulation.

III. Assembly of Heat Exchanger

The appearance of newly proposed dual packs fluid heat (DPH) exchanger driven by the proposed high frequency power conversion circuit is depicted in Fig. 3. This new spiral structure DPF heat exchanger works as a heat exchanger, with an end ring from a low resistance material, formed spirally by a thin plate of nonmagnetic stainless steel SUS316, which is inserted into the non metal vessel. The non-magnetic material SUS304 is selected as a material for the IH-DPH device due to the advantages it has such as uniform temperature distribution, excellent corrosion protection for low pressure moving in pipeline (water, vapor, gas, and powder).

The work coil uses enamel copper wire twisting together and isolated from each other. This work coil is called litz wire for power. In this IH heating device (see Fig. 3), thermally stable temperature of this wire is about 170 degrees centigrade. Actually, the water tube part is not over 120 degrees centigrade, because the heat insulating material is packed in IH-DPFH hot-water producer between work coil and IH heating element. This IH exchanger is based on the mechanism, which heats the low pressure continuous movement fluid in the pipeline tube by the heat exchanging action between IH heating element and fluid using the developed high frequency conversion circuit. Therefore, thermally stable temperature is also necessary for the pipeline tube. The fluid heating vessel tube uses the polycarbonate, and thermally stable temperature is below 120 degrees centigrade.

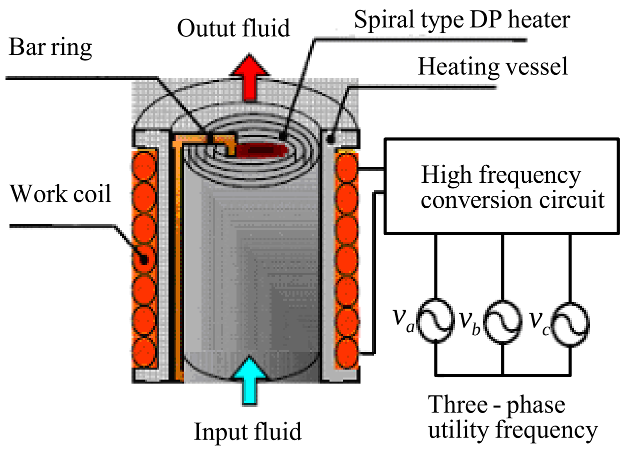


Fig. 3 Internal structure of DPFH exchanger

IV. Three-Phase High Frequency Conversion Circuit

A. Circuit Description

The novel circuit configuration of three-phase utility frequency to high frequency soft switching power conversion circuit proposed for high current IH applications is shown in Fig. 3. Three modules of singe-phase utility frequency to high frequency power converter is connected individually to each phase of the three-phase supply from one side and connected in parallel from the other side to the same terminals of IH load. Each single-phase module is composed of two power switching devices Q_1 (S_1/D_1) and Q_2 (S_2/ D_2), two diodes D_a and D_b, filter inductor L_1 in utility AC input-side, two capacitors C_1 and C_2 as active clamp resonance in accordance with IH load, low pass filter and lossless quasi-resonant snubber capacitor C_o. The work described hereafter concentrates on the three-phase topology of the conversion circuit. The operation modes are not discussed in this paper, as they have already been approached by the previous work [4]

V. Dual Mode Control

The proposed three-phase utility frequency to high frequency soft switching power conversion circuit uses a dual mode control of combining conventional PWM and PDM control for gating the power switching devices S_1 and S_2 of each single-phase module. The gating pulses are synchronized with the positive and negative half cycles of the corresponding phase voltage and they have to be exchanged every half cycle in synchronism with the polarity of the utility phase voltage to supply the desired power to the IH load. In addition, a dead time T_d is necessary between the gating signals of each phase power switching devices to avoid a shout through. The gating signal timing sequences during the positive and negative half cycles of phase are shown in Fig. 5. The output power is controlled by controlling the PWM duty cycle d_{PWM} as given in (11), which is determined by the duration of the on time T_{on1} of the main power switch to the high frequency switching period.

By introducing this control strategy, the proposed three-phase high frequency conversion circuit enables to supply the desired output high frequency power with ZVS operation to the IH load.

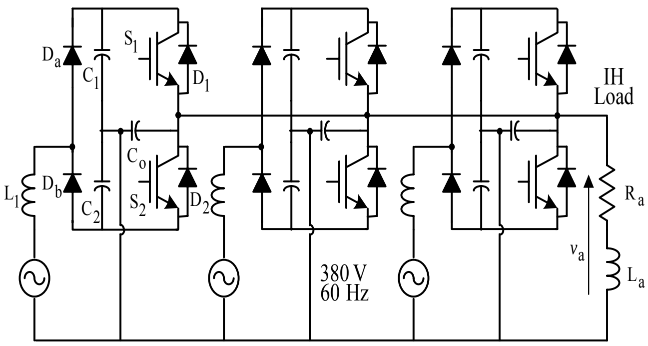


Fig. 4 High power IH conversion circuit using three single-phase modules connected to the same output

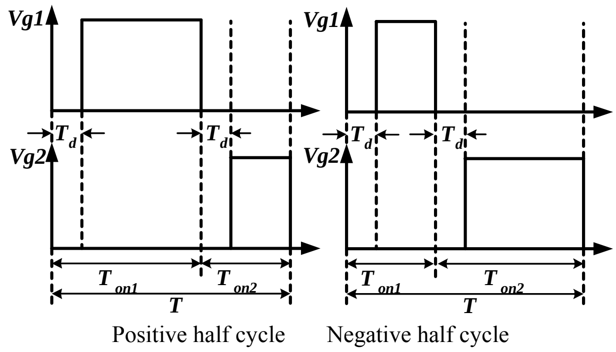


Fig. 5 Gating signals of PWM control scheme

$$d_{PWM} = \frac{T_{on1}}{T} \tag{11}$$

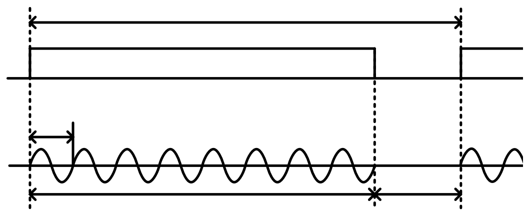


Fig. 6 Pulse density modulation control (d_{PDM} =0.7)

Besides to the PWM control, the proposed three-phase high frequency conversion circuit uses a pulse density modulation (PDM) or utility voltage integral-cycle control at low output power levels to extend the soft switching operation rang. In the PDM control the IH load current is gated to flow from the utility supply for an integral number of cycles (ON period) and then quenched for a few further number of complete cycles (OFF period) as depicted in Fig. 6 for a control period of 10 cycles utility power. The ZVS-based utility frequency AC-PDM time ratio as a control variable d_{PDM} is defined as given in (12). Thus, the effective IH load voltage is varied by controlling the ratio of the ON to the OFF cycles and the PDM duty cycle can be given as

$$d_{PDM} = \frac{T_{on}}{T_{on} + T_{off}} \tag{12}$$

In addition, the proposed three-phase high frequency conversion circuit can also regulates its high-frequency output power on the basis of dual-mode control of PWM and PDM control under a condition of complete ZVS conditions.

VI. Simulation and Experimental Results

The design specifications and circuit parameters of the experimental setup of the proposed three-phase utility frequency to high frequency conversion circuit using IGBT modules are indicated in Table I. The simulation and experimental results are described in the following.

TABLE I
Design Specification and Circuit Parameters

Item	Symbol	Value
Three-phase utility voltage	v_{ac}	$380V$, $60Hz$
Filter and resonant capacitors	C_1, C_2	$5\mu F$
Lossless snubbing quasi-resonant capacitor	C_o	$0.1\mu F$
Inductor of utility side filter	L_1	$1.0mH$
Effective resistance of IH load	R_a	1.65Ω
Effective Inductance of H load	L_a	$34.5\mu H$
Switching frequency	f_s	$20kHz$
Dead Time	t_d	$2\mu s$

Fig. 7 shows input voltage and current (phase a) waveforms of the proposed high frequency conversion circuit for different values of PWM duty cycles d_{PWM} of 0.4, 0.3, 0.2 and 0.1 respectively.

The relevant simulated and measured soft switching operating voltage and current waveforms near the peak value of utility voltage waveform for PWM control of the high frequency conversion circuit set up in case of a duty factor d_{PWM} = 0.5 are shown in Fig. 8. A very good quality and quantity agreement is obtained between the simulation and experimental voltage and current operation waveforms as it illustrated in Fig. 8.

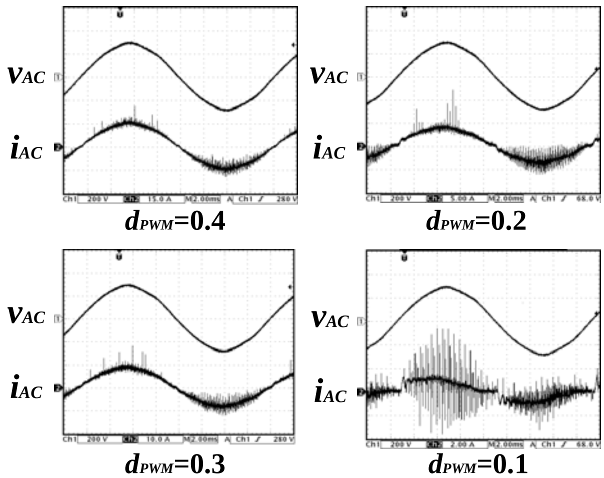
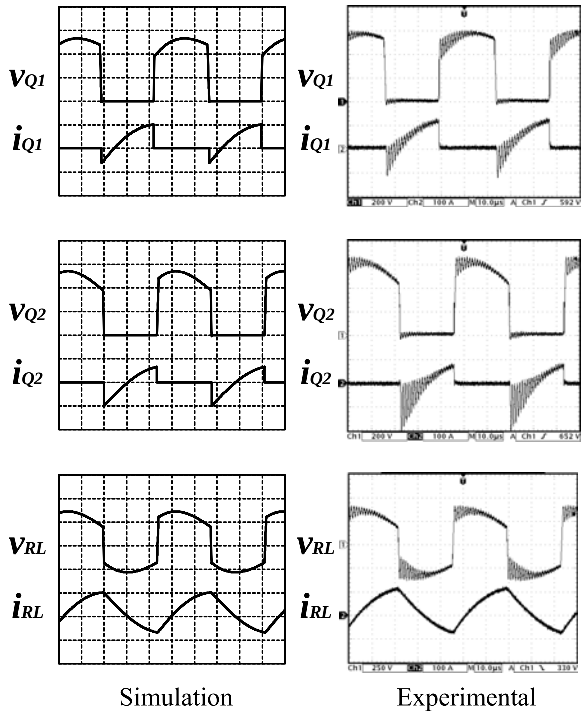


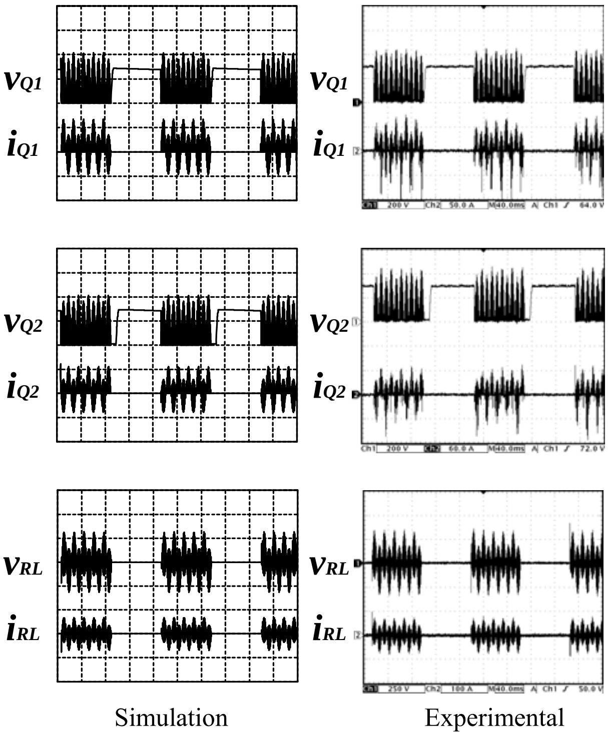
Fig. 7 Input (phase a) voltage and current waveforms for different PWM duty cycles



v_{Q1}, v_{Q2}: 200[V/div], v_{RL}: 250[V/div],
i_{Q1}, i_{Q2}, i_{RL}: 100[A/div], Time: 10[μs/div]

Fig. 8 Soft switching voltage and current waveforms in PWM control, d_{PWM} = 0.5.

From Fig. 7, it is clear to note that the input current waveform is much distorted at a low duty cycles d_{PWM} = 0.1. Therefore, the PWM control is more effective and suitable for high output power ranges of the proposed high frequency conversion circuit. However, the ZVS commutation operation can be realized over all the output power regulation area on the basis of dual mode control implementation in case of low power setting area using the utility frequency AC-PDM-ZVS control and the asymmetrical PWM control in case of high power setting area. The changing point of asymmetrical PWM and utility frequency AC PDM in this high frequency cycloinverter is set to be at a duty ratio of d_{PWM} = 0.3. In all the high frequency AC power regulation ranges, this high frequency cycloinverter operates in soft switching commutation by changing the control scheme changing from asymmetrical PWM control to PDM control at low duty ratios. The simulated and measured operating waveforms in case of dual-mode control in case of d_{PWM} = 0.3 and d_{PDM} = 0.5 are comparatively illustrated in Fig. 9.



v_{Q1}, v_{Q2}: 200[V/div], v_{RL}: 250[V/div], i_{RL}: 100[A/div], i_{Q1} 50[A/div], i_{Q2}: 60[A/div], Time: 40[μs/div]

Fig. 9 Soft switching voltage and current waveforms in case of dual-mode control, d_{PWM} =0.3, d_{PDM} =0.5.

The input power vs. the duty factor characteristics of this high frequency converter circuit under asymmetrical PWM control is depicted in Fig. 10. While, Fig. 11 shows the input power vs. the pulse density modulation characteristics of this high frequency converter circuit under the principle of dual-mode of asymmetrical PWM and pulse density control in case of d_{PWM} = 0.3.

The soft switching operation area of the high frequency converter circuit is also illustrated in Figs. 10 and 11. In Fig. 10, the high frequency cycloinverter controlled by the asymmetrical ZVS-PWM technique operates in a hard switching commutation operation mode in low power setting area. The soft switching operation range can be expanded as shown in Fig. 11. The high frequency cycloinverter controlled by dual-mode control of the asymmetrical PWM control and the utility frequency AC-PDM control operates completely in soft switching operation mode even in low power setting area. Therefore, the output power of this proposed high frequency power conversion circuit can be regulated up to about 150 W with ZVS soft switching operation using dual mode PWM and utility frequency PDM control.

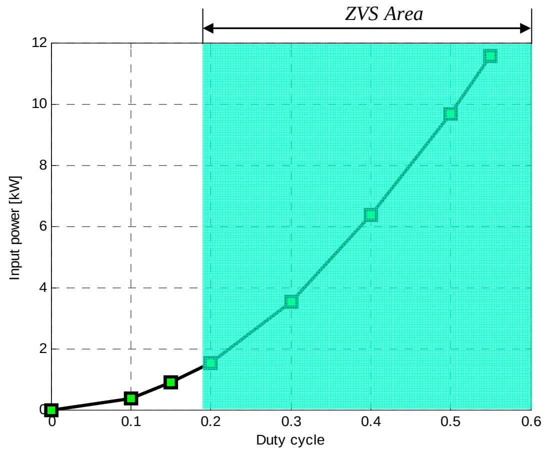


Fig. 10 Input power vs. duty cycle characteristic with PWM control.

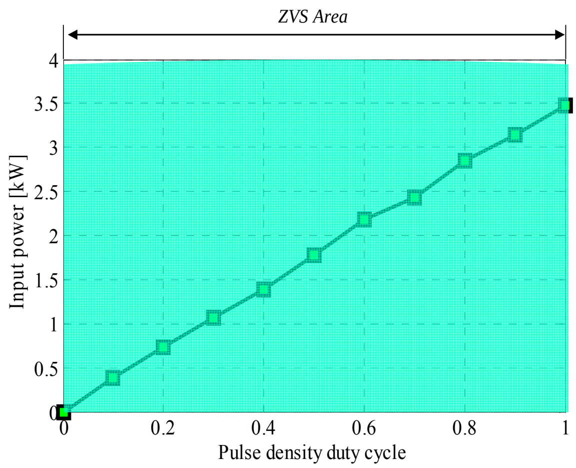


Fig. 11 Input power vs. ZVS-PDM characteristics in case of dual-mode control, d_{PWM} =0.3.

Fig. 12 illustrates the power conversion efficiency characteristics of the proposed three-phase high frequency conversion circuit under PWM control and dual-mode control. It is clear to note that the actual efficiency might be reduced in the low power setting area, due to the hard switching operation in low power setting range. The high conversion efficiency over 93% can be almost maintained when the dual-mode control of PWM and utility frequency PDM is used for low power setting area and the proposed conversion circuit can operate under a condition of complete ZVS conditions in all high frequency power regulation area. Therefore, the dual mode PWM/PDM is more effective to put it into practical use for the high-efficient power control implementation.

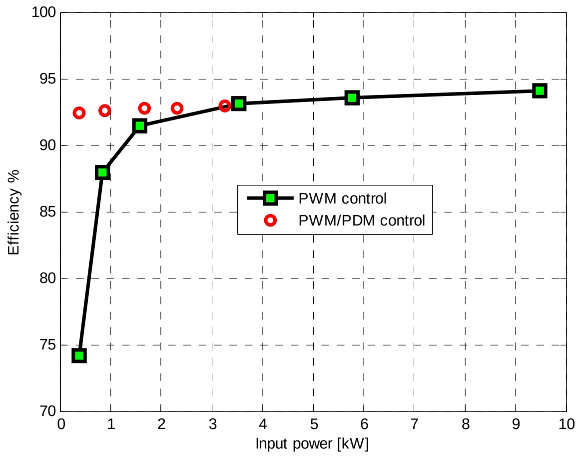


Fig. 12 Actual power conversion efficiency vs. output power characteristics with PWM and PDM control

VII. Conclusion

In this paper, a novel circuit topology of three-phase utility frequency to high frequency soft switching power conversion circuit with dual mode pulse width modulation and utility frequency pulse density modulation for high power induction heating applications has been newly proposed. This high frequency power conversion circuit is tested with a dual packs fluid heater heat exchanger designed for the hot water, steam and super heated steam producers, and it proves the features of compactness, low cost, high reliability, high efficiency and long life. High power conversion efficiency over 93% has been obtained with a dual-mode control. Experiment and simulation results are given to verify the operation principles and to evaluate its power regulation and conversion efficiency. The induction heated load is represented using mutual coupling model instead of equivalent transformer circuit model.

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