FUNDEMENTAL PRINCIPES OF WORKING IN RESONANT CONVERTER FOR INDUCTION HEATING

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ABSTRACT. In the paper has been given theoretical layout of the device for induction heating of the metals. Practical results on realized device show that the device can be used for regenerate of used metals, and for melting the copper concentrate with quality bigger than 60%. The results are procured on copper concentrate procured with extraction in the mine Bucim in Macedonia and Asarel in Bulgaria.

ОСНОВНИ ПРИНЦИПИ НА РАБОТА НА ВИСОКОЧЕСТОТНИТЕ ИНДУКЦИОННИ НАГРЕВАТЕЛИ
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РЕЗЮМЕ. В статията се предлага теоретично разработен проект на прибор за индукционно нагряване на метали. Практическите резултати от експерименталнния образец на прибора, показват че той може да се използува за топене на меден концентрат с качество (съдържание на мед) над 60%. Експериментите са проведени с меден концентрат доставен от рудниците Бацим, Македония и Асарел, България.

1. INTRODUCTION

All IH (induction heating) applied systems are developed using electromagnetic induction which was first discovered by Michael Faraday in 1831. Electromagnetic induction refers to the phenomenon by which electric current is generated in a closed circuit by the fluctuation of current in another circuit placed next to it. The basic principle of induction heating, which is an applied form of Faraday's discovery, is the fact that AC current flowing through a circuit affects the magnetic movement of a secondary circuit located near it. The fluctuation of current inside the primary circuit provided the answer as to how the mysterious current is generated in the neighboring secondary circuit. Faraday's discovery led to the development of electric motors, generators, transformers, and wireless communications devices. Its application, however, has not been flawless. Heat loss, which occurs during the induction heating process, was a major headache undermining the overall functionality of a system. Researchers sought to minimize heat loss by laminating the magnetic frames placed inside the motor or transformer. Faraday's Law was followed by a series of more advanced discoveries such as Lentz's Law. This law explains the fact that inductive current flows inverse to the direction of changes in induction magnetic movement. Heat loss, occurring in the process of electromagnetic induction, could be turned into productive heat energy in an electric heating system by applying this law. Many industries have benefited from this new breakthrough by implementing induction heating for furnacing, quenching, and welding.

In these applications, induction heating has made it easier to set the heating parameters without the need of an additional external power source. This substantially reduces heat loss while maintaining a more convenient working environment. Absence of any physical contact to heating devices precludes unpleasant electrical accidents. High energy density is achieved by generating sufficient heat energy within a relatively short period of time.

The demand for better quality, safe and less energy consuming products is rising. Products using IH include electronic rice cookers and pans. Safe, efficient and quick heating appliances attract more customers. This document describes induction heating, power systems, and IH applications.

2. BASICS OF INDUCTION HEATING

Induction heating is comprised of three basic factors: electromagnetic induction, the skin effect, and heat transfer. The fundamental theory of IH, however, is similar to that of a transformer. Electromagnetic induction and the skin effect are described in this section. Figure 2-1 illustrates a very basic system, consisting of inductive heating coils and current, to explain electromagnetic induction and the skin effect. Figure 2-1-a shows the simplest form of a transformer, where the secondary current is in direct proportion to the primary current according to the turn ratio. The primary and secondary losses are caused by the resistance of windings and the link coefficient between the two circuits is 1. Magnetic current leakage is ignored here. When the coil of the secondary is turned only once and short-circuited, there is a substantial heat loss due to the increased load current (secondary current). This is demonstrated in Figure 2-1-b.

Figure 2-1-c shows a system where the energy supplied from the source is of the same amount as the combined loss of the primary and secondary. In these figures, the inductive coil of the primary has many turns while the secondary is turned only once and short-circuited. The inductive heating coil and the load are insulated from each other by a small aperture. The next phase of the skin effect occurring under high frequency is presented in Section 2-2. As the primary purpose of induction heating is to maximize the heat energy generated in the secondary, the aperture of the inductive heating coil is designed to be as small as possible and the secondary is made with a substance featuring low resistance and high permeability. Nonferrous metals undermine energy efficiency because of their properties of high resistance and low permeability.

2-1. Electromagnetic Induction

As shown in Figure 2-1, when the AC current enters a coil, a magnetic field is formed around the coil according to Ampere's Law.

$$\int Hdl = Ni \qquad (2\text{-}1)$$

An object put into the magnetic field causes a change in the velocity of the magnetic movement. The density of the magnetic field wanes as the object gets closer to the center from the surface. According to Faraday's Law, the current generated on the surface of a conductive object has an inverse relationship with the current on the inducting circuit as described in Formula 2-2. The current

on the surface of the object generates an eddy current.

$$E = -\frac{d\varphi}{dt} \qquad (2\text{-}2)$$

As a result, the electric energy caused by the induced current and eddy current is converted to heat energy as shown in Formula 2-3.

$$P = \frac{E2}{R} = \frac{I2}{R} \qquad (2\text{-}3)$$

Here, resistance is determined by the resistivity (ρ) and permeability (μ) of the conductive object.

Current is determined by the intensity of the magnetic field. Heat energy is in an inverse relationship with skin depth which is described in Section 2-2.If an object has conductive properties like iron, additional heat energy is generated due to magnetic hysteresis. The amount of heat energy created by hysteresis is in proportion to the size of the hysteresis. In this document, this additional energy is ignored because it is far smaller (less than 10%) than the energy generated by induction current.

2-2. Skin Effect

The higher the frequency of the current administered to the coil, the more intensive is the induced current flowing around the surface of the load. The density of the induced current diminishes when flowing closer to the center as shown in Formula 2-4 and 2-5 below. This is called the skin effect or kelvin effect. From this effect, one can easily infer that the heat energy converted from electric energy is concentrated on the skin depth (surface of the object).

$$Ix = i \, e^{-\frac{x}{do}} \qquad (2\text{-}4)$$

where,

ix: distance from the skin (surface) of the object, current density at x.

Io: current density on skin depth (x=0)

do: a constant determined by the frequency (current penetration depth or skin depth)

ω: Frequency of the current flowing through the object

Formula 2-5 states that the skin thickness is determined by the resistivity, permeability, and frequency of the object.
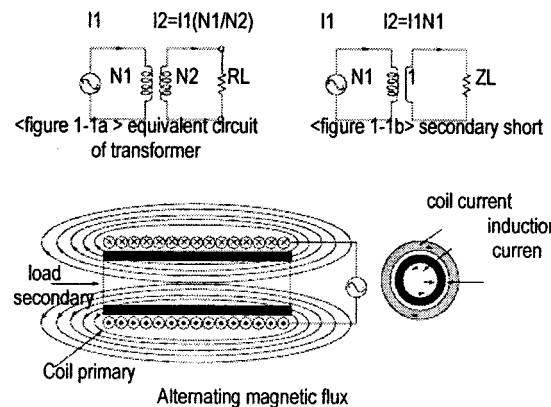

<figure 1-1a > equivalent circuit of transformer

<figure 1-1b> secondary short

Fig. 2-1: Basics of Induction Heating

$$do = 2\sqrt{\frac{2\rho}{\mu\omega}} \qquad (2\text{-}5)$$

where,

ρ: resistivity

μ: permeability of the object

ω: Frequency of the current flowing through the object

Formula 2-5 states that the skin thickness is determined by the resistivity, permeability, and frequency of the object.

3. TOPOLOGY OF POWER SYSTEM

Generally, semiconductor switching devices operate in Hard Switch Mode in various types of PWM DC/DC converters and DC/AC inverter topology employed in a power system. This process results in switching loss. The higher the frequency the more the switching loss, which obstructs efforts to raise the frequency. Switching loss can be calculated in a simple way as shown in Formula 3-1 below. Switching also causes an EMI problem, because a large amount of di/dt and dv/dt is generated in the process.

$$PSW = \frac{1}{2} VSWISWfS \, (ton + toff) \qquad (3\text{-}1)$$

where,

Psw : switching loss [W]

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Vsw : switching voltage [V]

Isw : switching current [A]

fs : switching frequency [kHz]

ton : switch turn-on time [s]

toff : switch turn-off time [s]

By raising the switching frequency, you can reduce the size of a transformer and filter, which helps build a smaller and lighter converter with high power density. But as presented earlier, switching loss undermines the efficiency of the entire power system in converting energy, as more losses are generated at a higher frequency. Switching loss can be partly avoided by connecting a simple snubber circuit parallel to the switching circuit. However, the total amount of switching loss generated in the system remains the same. The loss avoided, has in fact, just moved to the snubber circuit. Higher energy conversion efficiency at high frequency switching can be obtained by manipulating the voltage or current at the moment of switching to become zero. This is called "Soft Switching", which can be subcategorized into two methods: Zero-voltage switching and Zero-current switching. Zero-voltage switching refers to eliminating the turn-on switching loss by having the voltage of the switching circuit set to zero right before the circuit is turned on. Zero-current switching is to avoid the turn-off switching loss by allowing no current to flow through the circuit right before turning it off. The voltage or current administered to the switching circuit can be made zero by using the resonance created by an L-C resonant circuit. This topology is named a "resonant converter." In Zero-current switching, the existing inductance is absorbed into the resonant circuit, eliminatin the surge in voltage in a turn-off situation. A voltage surge resulting from an electric discharge of junction capacitance, which occurs upon turning on the switching circuit, cannot be avoided. This method has a defect of causing switching loss (0.5CV2f). Zero-voltage switching, however, is free from such a defect by making both the existing inductance and capacitance to be absorbed by the resonant circuit. This eliminates any chance of causing a surge in current both at turn-off (caused by inductance) or turn-on (by capacitance) conditions. Zero-voltage switching enables switching with less loss while substantially reducing the problem of EMI at high frequency. This difference in features make Zero-voltage switching more desirable than Zero-current switching.

3.1 Resonant Converter

The resonant circuit of a resonant converter consists of a capacitor, an inductor, and resistance. Two types of resonant converters are generally used: a series resonant circuit and a parallel resonant circuit. For resonant frequency of the amount of energy stored in the capacitor to be sent to the inductor. Resonance occurs while the inductor and the capacitor exchange the energy. The total amount of energy stored in the circuit during resonance remains unchanged. This total amount is the same as the amount of energy stored at peak in the conductor or capacitor. Fig. 3-1 is full bridge converter for induction heating.

Fundamental principle that in the de sign of a small - sized electrical equipment, the voltage and current in the circuit must be operated with a high frequency. This can be achieved by operating the switching device of the circuit with a switching frequency of the level of tens or hundreds of kilohertz. By this method, there will be some power loss in the circuit in terms of switching loss that tends to increase with the switching frequency. To eliminate the switching loss with high switching frequency, the conventional circuit with hard switching operation will be replaced by a resonant circuit with soft switching or zero voltage switching operation (ZVS). In some applications, the output power control can be achieved by controlling the pulse width of the square wave output voltage, using the phase-shift control between the gate signal of each branch of a single-phase full-bridge inverter. In case of an ideal MOSFET switching device without stray capacitance (Coss), during increase of phase shift for reducing output power,   the
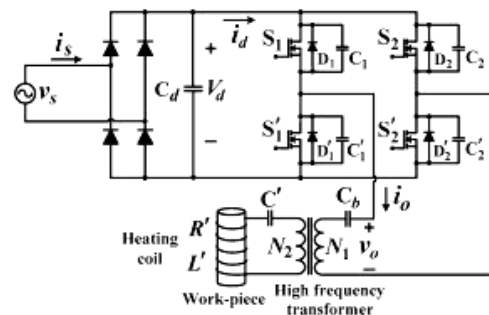

Fig 3-1. Full-bridge inverter-fed induction heating.

switching frequency must always be slightly increased in order that the phase angle of output current never leads both the positive and negative front edges of the output voltage waveform], but the phase angle must always lag the front edges so as to allow the regenerative mode to occur or the body diode of the next-coming turn-ON ideal MOSFET switch to conduct before the powering mode of circuit operation; otherwise, the inverter circuit will be driven away from the condition of ZVS (NON-ZVS). For the practical switching device with Coss, the switching frequency must be increased slightly further when compared with the case of the aforementioned ideal switching device in order to still maintain the operating condition of ZVS by making a complete discharge from Coss before the next-coming turn-ON time of the same switching device. The detailed analysis to explain the internal operating mechanism of the circuit during the charge–discharge process of the four switch capacitors (Coss) of the full-bridge inverter, both by mathematical calculation and experimental verification, has not been presented. So, how to analyze the circuit operation during the charge–discharge process by calculation with experimental verification is the aim of this research. In order to solve this problem, the single-phase full-bridge series resonant inverter with a load of induction heating has been developed in our laboratory, as shown in Fig.3-1, to verify the principle proposed in this paper by experimental results.

In case of an ideal switching device without Coss , there will be only one region of phase-shift control angle (0 < ф), while reducing the output power from its maximum value; but in the practical case with a certain value of Coss , the phase-shift control angle (0 < ф) will be divided into two different operating regions. In the first region, where the phase shift φ lies over the

range of φm in $\leq \varphi$ (hereinafter referred to as the conventional phase shift), the charge–discharge will occur in each of the two branches between the upper and lower capacitors, as indicated by ③ ⑤ and ③′ ⑤′ in the upper waveform of Fig. 3-2(a) and (b). For the second region, with the control range of phase shift $0 \leq \varphi \leq \varphi m$ in , the charge–discharge process becomes quite different from that of the first region. The circuit operation over this region is under a changing condition of mode of circuit operation from the conventional phase shift to zero phase shift (hereinafter referred to as the transition phase shift). For the phase shift with control angle over the range of $0 \leq \varphi \leq \varphi m$ in , the charge–discharge process will be mixed with both the case of one-branch charge–discharge process for two short time durations, as indicated by ③ ⑤ and ③′ ⑤′ in the lower waveform of Fig. 3-2(c) and also with only the case of the two-branch charge–discharge process for one short time duration, as indicated by ④ and ④′ nd in the lower waveform of the same figure. At the end point of phase-shift control angle, which is the position of zero phase shift ($\varphi = 0$), there will be the case of only the two-branch charge–discharge process, as shown in Fig.3- 2(d). The minimum phase shift (φmin) in Fig. 3-2(a)–(d) is the boundary position between the conventional phase-shift and the transition phase-shift control regions. The output voltage waveform at this position of minimum phase-shift control (φmin) can be shown in Fig.3- 2(b). The principle proposed can be applied to the series resonant inverter using the principle of phase shift for output power control. In this application, the circuit designer must consider correctly the relationship between the phase-shift angle (φ) and the operating frequency (fs); especially in case of higher rating of MOSFET power switching device that has a higher value of $Coss$, the switching frequency must be designed to be higher than for the case of lower rating of power switching device, when considering at the same phase-shift angle or same output power level, in order to maintain the circuit to operate under the same operating condition of ZVS and to protect all the switching devices from not being damaged.
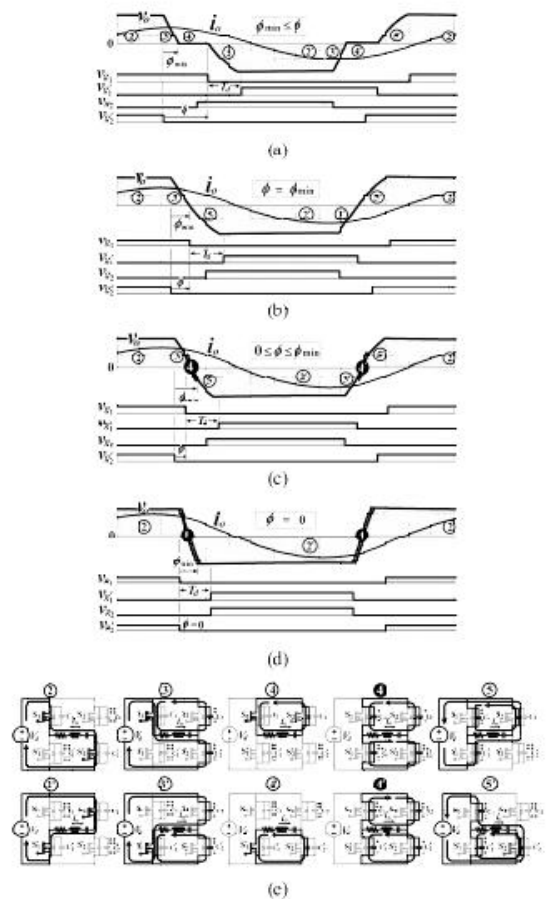

Fig. 3-2. Analyze the charge transfer process of the inverter switches under two different operating regions of phase shift φ : (a) and (b) for the first region of phase shift φm in $\leq \varphi$, and (b)–(d) for the second region of phase shift $0 \leq \varphi \leq \varphi min$.

4.CONCLUSION

The inverter circuit operation with two regions of conventional phase shift and transition phase shift under ZVS and NON-ZVS conditions for induction heating can be concluded as follows.

1) In case of an ideal MOSFET switching device without stray capacitance ($Coss$), during phase-shift control, the switching frequency must always be slightly increased in order that the phase angle of output current never leads both the positive and negative front edges of the output voltage waveform; otherwise, the inverter circuit will be driven away from the condition of ZVS (NON-ZVS). For the practical switching device with $Coss$, the switching frequency must be increased slightly further when compared with the case of the aforementioned ideal switching device in order to still maintain the operating condition of ZVS by making a complete discharge from $Coss$ before the next-coming turn-ON time of the same switching device.

2) In the control range of the transition phase shift with $\varphi <$ φmin, the charge transfer occurs in both one-branch and two-branch switch capacitors, while in the control range of conventional phase shift with $\varphi min \leq \varphi$, the charge transfer of two-switch capacitors occurs only in one branch of the switch capacitor. Although, the charge transfer process in these two regions of phase shift φ is quite different, the continuous

characteristic curves of the four critical parameters between these two cases can still be obtained, as shown in the graphs.

3) In the control range of conventional phase shift $\phi_{min} \le \phi$, where charge transfer occurs only in one branch, each capacitor voltage changes between 0 and $+Vd$, and the output voltage changes between 0 and $+Vd$ and also between 0 and $-Vd$, which results in the same rate of change of output voltage as that of the capacitor voltage. On the other side of the phase-shift control range, $\phi \le \phi_{min}$, which is the region of transition phase shift, where the two branch charge transfer occurs and the rate of change of the output voltage becomes twice that of the capacitor voltage.

4) For the variable region of phase shift $0 \le \phi$, the beginning and ending points of the charge transfer for each pair of switch capacitors in the same branch will not be at the same time, but will depend on the time instant the turn-OFF signal is initiated. In this case, the turn-OFF signal of the second branch is initiated before the first branch; therefore, the charge transfer in the second branch will terminate before the first branch. Consequently, the switches in the first branch will be damaged in case the NON-ZVS operating condition occurs in the circuit [see Fig. 2(a)–(d)]. Without phase-shift control ($\phi = 0$) or in case of a conventional square wave, the turn-ON and turn-OFF signals will be initiated at the same time instant; therefore, the beginning and ending points of charge transfer will be at the same time, and consequently, all the switches in both branches will be damaged due to NON-ZVS operation in the circuit.

5) In the paper has been given theoretical layout of the device for induction heating of the metals. Practical results on realized device is in power of 60kW and melting 100kg copper.

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Also the device can be used for regenerate of used metals, and for melting the copper concentrate with quality bigger than 60%. The results are procured on copper concentrate procured with extraction in the mine Bucim in Macedonia and Asarel in Bulgaria. With this metod we obtain copper with 99.9% Cu quality. 6) The results from this paper can be used for constraction on devices for induction heating with power from 500kW.

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