The Critical Factors & Loading Features in Design Inductive Heating-Device

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Abstract: - The inductive heating technique has been studied popularly by many scholars all over the world. Today the inductive heating facilities have been applied in many manufacturing tools of many fields in Taiwan, and this promoted research in this field directing to higher power, higher frequency, and higher efficiency as well. This study was pilot study for practical design of resonated heating circuit with half-bridge resonated inverter, especially some critical factors when considering the loading features including its primary theory, skin effects, permeance, conductance, and loading features. With this pilot-study, we would implement it into our further advanced research in high-power heating facilities with Half-Bridge Resonated Inverter.

Key-Words: - Inductive Heating, Half-bridge Resonated Inverter, Working Objects (cooking vessels).

1. Introduction

Owing to the progress of semi-conductor components in recent decades, more power elements could be applied in products of higher-power device. So as well the increase of endurance of voltage and ampere of components prompted the rapid development of power electronics field. That leads to higher frequency, response, and efficiency performance of a larger capacity heating device. Especially the popular application of inductive heater was in illustration of the development of industry. Since the heating methods such as gas or electricity in family would leak heat around the heater itself, the heater got lower energy transformed efficiency. The inductive heating method which uses rectifiers and high frequency inverter to convert 60Hz AC input current into 20~40KHz high frequency energy output to supply the inductive coils which would generate the inductive eddy current so as to heat the pan over coils [1].

Nowadays the power electronic technique is to implement the electronics into huge power circuits or systems. So to speak, it's a process how to deal with power transformation with semiconductor components. Electronic technique has been developed since the first Silicon Control Rectifier (SCR) was invented in 1956. Today power electronics can be divided into Traditional and modern stage. The former was mainly developed power capability with SCR such as fast-speed SCR, inversed-conduct SCR, bi-direction SCR etc. Not with standing the improvement with parameter as voltage, current, dv/dt, di/dt, and switching feature, yet there were many choke points such as lack of ways of up-grade running frequency. That led to add capacities, conductors, and some auxiliary switches in circuits, and led to improper size of products and in-application controlled frequency, and finally the new generation electronic technique was initiated.[2]

The most easily damaged components in power electronic driver circuits are switching ones, and under the consideration of both high voltage and current endurance and easily driven, the related design were mainly taken advantage of Insulated Gate Bipolar Transistor-IGBT and Power MOSFET. IGBT owns features of high speed, driving capability, and input resistance, so was viewed as most proper for high power switching components. In addition, it also owns high voltage endurance at off condition while loading high current at on condition. But IGBT has two defects, one is huge off current and longer delay time that lead to much waste power and the other is latch-up effect, that would causes out of control of Gate polar or even complete damage to components. Sum up, the purpose of this study is to design a high power stable heating device with safety and intelligence. Generally speaking, An intelligent and stable high power magnetic inductive heating facility with IGBT as switching components would provide well protection for driver circuit to avoid damage of components even under any troubleshooting including incorrect programming, and this performance would be the motivation of this study. [5]

Since magnetic inductive heating facility belongs to application of high frequency electronic power components which combine of both inerter and technique of switching so as to convert low frequency DC power into high frequency AC power. Finally, crossing the coils with changed magnetic field and generating eddy current on the surface of cooking vessels, in the process, through coupled magnetic field to convert electric energy into magnetic energy, further more convert magnetic energy into heat transferred to loads to accomplish heating effect. But, the higher frequency of switching components is, the more switching lose is. Driving signal couldn't control on and off of IGBT on account of latched effect resulting from over-loading and noise, and this condition led to damage of IGBT themselves and larger stress of components resulting from current or voltage glitches[1]. So how to design a high frequency, power, and performance inverter with Zero-Voltage-Switching (ZVS) is the purpose of this main research. But in this paper, we not only consider system circuits viewpoint, but also we consider from basics of materials making of inductive heating facilities.

2. Inductive Heating Primary Theories

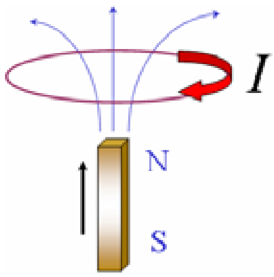

Fig. 1 Basics of electrical-magnetic inductive field [1]

Inductive heating mainly based on electrical-magnetic inductive phenomenon presented by Faraday in 1831, in which interpreted that the change of magnetic field would generate electricity, and if a loop of conductor existed in a change magnetic field could produce inductive electrical field that would induce inductive electromotive force and inductive current in this loop as in Fig. 1. In an area surrounded by closed loop, if magnetic field occurred to any change, there would be inductive current in this closed loop which was called inductive current. According to Lenz's Law, the direction of the inductive current would be easily figured out and many applications had been developed based on this rule such as transformer.

Supposed that we put a conductor in a changing magnetic field that was changed based on time interval, the density of line of magnetic force would change, and according to Lenz's law the conductor would generate inductive current to against the change of the density of line of magnetic force, consequently, this generated current was called eddy current as shown in Fig. 2.

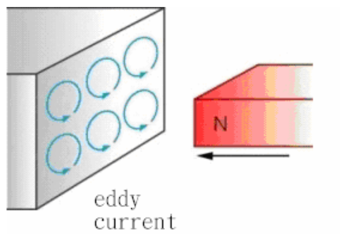

Fig. 2 Basics of eddy current [1]

Furthermore, according to Ampere's circuital law the strength of constructed magnetic field surrounding the long electrical conductor was positive ratio to the scale of current flowing in the conductor while negative ratio to the distance with the conductor. According to the Ampere's right-handed screw rule, we can easily know the direction of magnetic field, so if we wanted to get direction-changed magnetic field, there must be direction-changed current flow in the conductor. Fig. 3 was the inductive heating conception. The heating coils would flow through high-frequency, direction-changed AC current to generate direction-changed magnetic field. The direction of magnetic field would continuously stepping after AC current, When working objects were located in this magnetic field and was affected by the direction-change of magnetic field, moving electronics in working objects would be inductive by field and generate circulated movement to generate opposite magnetic field to against or offset coils' magnetic field according to the Lenz's law. This movement of moving electronics was called eddy current. Since there was resistance in working objects, working objects would generate heat when eddy current flowed inside the objects. The power produced in objects could be figured out according to Joule's Law as $P_v = \rho J^2$, ρ was resistance constant and J was current density [2].

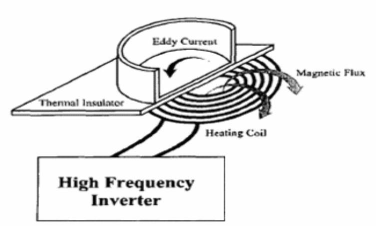

Fig. 3 Basics of inductive heating [5]

2.1 Skin-effect

The induced eddy current on working object will centralize on over the surface, and the higher frequency operated in heating coils is, the more obviously the eddy current centralizes over the surface. This phenomenon was called Skin Effect [1]. Depth of Skin Effect δ would be showed in formula 1, and the density of eddy current would gradually decrease when being far away the working object surface as shown in formula 2

$$\delta = \sqrt{\frac{1}{4\pi * 10^{-7}}} * \sqrt{\frac{\rho}{\mu_r f}} \qquad (1)$$

where μ_r is a permeance constant, f is frequency, and ρ is a resistance constant.

$$J_x = J_0 * e^{(-x/\delta)} \qquad (2)$$

where J_x is the current density from surface to center x, J_0 is the current density of location x=0, δ is a current density, and x is the distance from objects surface to center.

2.2 Permance Rate

The movement of electronics around the out orbits of the atomic nucleus leads to generating magnetic force of materials and electronics itself rotate clockwise or counterclockwise would produce magnetic moment, and both movements would generate magnetic torque. If both moved non-symmetrically, magnetic torque would generate. Some of the magnetic torques would combine into magnetic field. The smallest permanent magnetic unit queued in directions that were out of order, and if they were forced by out magnetic field, they would cline to regular direction, therefore it was called magnetization. Permance capability of materials could be divided into four classifications according to relative permance constant μ_r as follow:

1. Iron-magnetic materials, while μ_r was far larger than 1, and also called strongly magnetic materials

such as iron, copper, nickel, stain, and cobalt.

2. Sub-magnetic materials, while μ_r was little larger than 1, and was called normal magnetic materials such as platinum, tin, aluminum, and air.
3. Non- magnetic materials, while μ_r was less than 1, such as vacuum.
4. Anti- magnetic materials, while μ_r was far less than 1, such as gold, brass, silver, carbon, and lead.

Regarding with all kind of magnetic materials, it was not necessary for them to be magnetic at any temperature. Generally speaking, there was a threshold temperature, and above this temperature, atoms magnetic torque was completely out of order because of briskly movement of atoms under high temperature. On the other hand, under this temperature, atoms magnetic torque was in order sequence, so objects would be self-magnetic and became iron-magnetic feature.

Scale of permance $B=\mu_0(H+M)$， in this formula, H was magnetization strength and M was strength of magnetic field, and μ_0 was permance rate in vacuum, magnetic induction strength was also called magnetic density（T）。permance rate $\mu=\dfrac{B}{\mu_0 H}$ was ratio of any point B over H on magnetization curve.

Permance rate [1] represented the degree of magnetization for magnetic materials or sensitivity of reaction of materials to out magnetic field. The chemical components of materials and alloy, heat-processing, frozen-processing, and temperature all will affect on the permance. As for iron-magnetic materials, the strength of inductive magnetic field on the surface would increase following the permance increase.

2.3 Close Effect

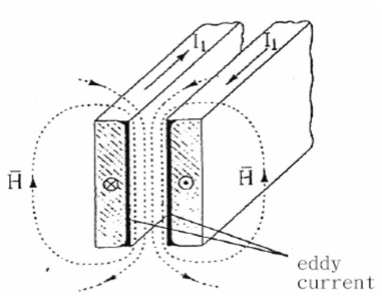

Fig. 4 Relationship between heating coils and path of inductive current [3]

Close effect [3] meant that since the current direction was different in two close conductors (coils) or electrical objects, there was a relative effect of changed magnetic field, which would affect magnetic force to change. This kind of effect was proved inductive path model almost the same as inductive coils like Fig. 4. The higher was the frequency and the less was the distance between working object and heating coils, the more obvious was the close effect. At the time, the generated eddy current would reinforce magnetic lines density through area of conjunction of both, and the heating capability was increased gradually. But it was worthwhile to pay attention to skin effect that would only affect the spread of eddy current in working object rather than the scale of eddy current affected by close effect.

3. Load features

Main factors that affect load features were the distance between working object and heating coils, resistance constant of working object, and permance constant. Those would be discussed as follow:

3.1 Cooling down and isolation of heating coils

In the heating process, if the temperature were too high, the coils would be burnt down. There were two factors that made the temperature of coils rise up, one was the loss during current flowing through coils, and the other was radiation heat produced by working objects when heating. The ordinary cooling down methods were self-cooling, water-cooling, oil-cooling, and air-cooling.

To upgrade the coupling degree and speeding heating process, the distance between working object and heating coils must keep as close as possible, but avoid causing short by little trash iron on the surface of working object, it was suggested to paint with a layer of epoxy resin on the surface of working objects.

3.2 The distance between working object and heating coils

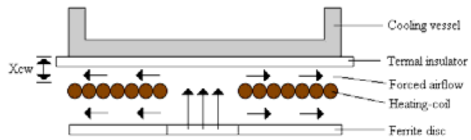

Fig. 5 The distance between working object and heating coils [4]

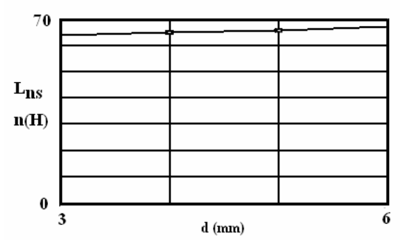

Fig. 6 Equivalent inductance generated by distance between working object and heating coils [4]

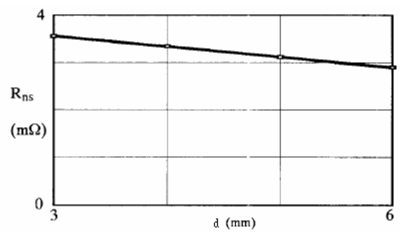

Fig. 7 Equivalent resistance generated by distance between working object and heating coils [4]

Fig. 5 was shown the distance between working object and heating coils, d was stands for the distance. The closer was the distance, and the more was the coupling magnetic force density. But to avoid too high temperature on heating coils, we still to keep enough space to let air flow for cooling down the temperature. From Figs. 6 and 7, we could learn the influence causing by the gap on equivalent inductance and resistance of working object. That was if the distance increased, the equivalent inductance would increase but resistance decrease.[4]

3.3 Resistance and permance constant of working objects

Electrical parameters of working objects had much to do with their materials. For instance with iron and aluminum, and we could easily learned those electrical parameters of working objects made of iron and aluminum under operating frequency 20 KHz as shown in Table 1.

Table 1 Electrical parameters of iron and aluminum under operating frequency 20 Khz [5]

Electrical parameters	Iron	Aluminum
Resistance constant	$9.8*10^{-8}$	$2.5*10^{-8}$
Relative permance	100	1
Depth of skin effect	0.11	0.56

From Table 1, we could know that sub-magnetic materials like aluminum and magnetic materials like iron have lower resistance constant and permance, so if we wanted to enhance output power of heating facilities made of sub-magnetic materials, we had to increase the operating frequency of current in heating coils and numbers of heating coils.

Fig. 8 was output current features of heating coils made of iron and aluminum under different operating frequency, and we could get two conclusions as following:

1. If we wanted to gain the same output current with different materials of heating coils, the inductive heating facility system must operate under higher frequency.
2. If the system operated under higher frequency, the sensitivity of output current would be high.

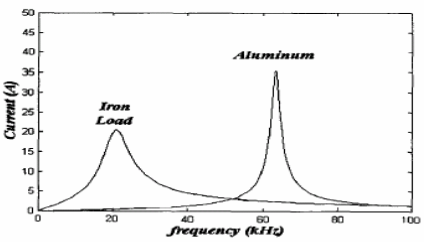

Fig. 8 Relationship between frequency and output current with different materials [5]

3.4 Resistance features of working objects

Most of the resistance features of working objects have liner relationship with temperature change, and its relationship can be described as following [3]:

$$\rho_\theta = \rho_1[1+\alpha(\theta-\theta_1)] \tag{3}$$

where ρ_θ is a resistance constant of working objects at θ, ρ_1 is a resistance constant of working objects at θ_1, and α would be different according to different working object.

If a working object were liner change, the relationship described above can be changed as following:

$$\rho = \rho_1 + \frac{\theta-\theta_1}{\theta_2-\theta_1}(\rho_2-\rho_1) \tag{4}$$

Table 2 provided reference data of α, $\rho_{20\ ^oc}$ and melt point of different materials of working objects and Fig. 9 was resistance constant of different material of working objects under variable temperature.

Table 2 α, $\rho_{20\ ^oc}$, and melt point of different working objects [3]

Working objects	∂	ρ_{20° (Ω-m)	Melt point (^{0}C)
Aluminum	$4.29x10^{-3}$	$2.65x10^{-8}$	660
Copper	$3.93x10^{-3}$	$1.72x10^{-8}$	1084
Iron	$6.5x10^{-3}$	$9.71x10^{-8}$	1538
Silver	$4.1x10^{-3}$	$1.59x10^{-8}$	962
Bronze	$1.86x10^{-3}$	$3.9x10^{-8}$	1046
Braze	$1.6x10^{-3}$	$6.4x10^{-8}$	931

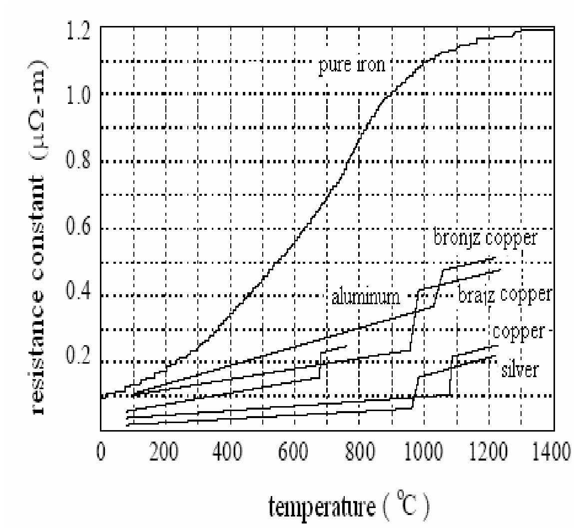

Fig. 9 Resistance constant of different material of working objects under variable temperature [3]

4. Inductive-heating equivalent circuit

The equivalent circuit is almost the same as the transformer equivalent circuit, and the transformer equivalent circuit was shown in Fig. 10. The difference between them is that the secondary winding coils of inductive-heating circuit can be considered as transformer equivalent circuit with only one coil of secondary winding coils, and the conception was transferred into Fig. 11. Z_L is the resistance of working object (pans on inductive-heating facilities).

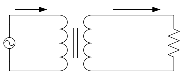

Fig. 10 Equivalent circuit model of transformer [1]

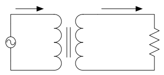

Fig. 11 Equivalent circuit model of inductive-heating [1]

The parameters of loading usually are affected by those factors as shape of heating coils, the distance between coils and working objects (pans), the materials of working objects, conductance rate of working objects, permeance rate of working objects, and the operating frequency *f* of the system. The heating coils are also affected by inductance value, coil length, and the permeance constant and area of coils. In Fig. 12, the system considered the equivalent resistance and coupling factor M of heating coils. R_L could be gained from depth of skin-effect of eddy current.

$$R_L = \frac{\rho}{\delta} = K\sqrt{\rho\,\mu_t\, f} \qquad (5)$$

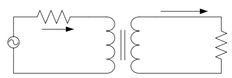

Fig. 12 Equivalent circuit considered with coils resistance and coupling constant [5]

In Fig. 13, an equivalent circuit was primary winding coils equivalent to secondary winding coils. *Leq* is equivalent inductance and *Req* is equivalent resistance.

$$L_{eq} = L_1 - \frac{(wM)^2\ L_2}{R_L^{\ 2} + (wL)^2} = L_1 - A^2\ L_2 \qquad (6)$$

$$R_{eq} = L_1 - \frac{(wM)^2\ R_L}{R_L^{\ 2} + (wL)^2} = r - A^2\ R_L \qquad (7)$$

$$A = \frac{wM}{\sqrt{R_L^{\ 2} + (wL_2)^2}} \qquad (8)$$

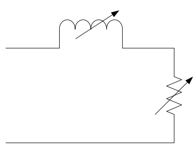

Fig. 13 Equivalent circuit from second winding to primary [5]

5. Conclusions

The induced eddy current on working object will centralize on over the surface, and the higher frequency operated in heating coils is, the more obviously the eddy current centralizes over the surface. This phenomenon was called Skin Effect.

Permance rate represented the degree of magnetization for magnetic materials or sensitivity of reaction of materials to out magnetic field. The chemical components of materials and alloy, heat-processing, frozen-processing, and temperature all will affect on the permance. As for iron-magnetic materials, the strength of inductive magnetic field on the surface would increase following the permance increase.

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There were two factors that made the temperature of coils rise up, one was the loss during current flowing through coils, and the other was radiation heat produced by working objects when heating. If the distance increased, the equivalent inductance would increase but resistance decrease.

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