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Design and Comparison of Conductor Size for Induction Cooker Coil

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Abstract: The use of induction heating in industrial applications is old and wide. In recent years, this technology was entered to domestic use. The induction cookers use induction heating for cooking. The induction cookers come in a variety of forms. In this paper, it deals with the design of pancake coil used in induction cooker and compares the coil size of calculated results. This coil is composed of 19 strands and it is twisted. The metal of conductor is used with copper because copper is the best of conductive material. The results are presented as general curves for three sizes of wires (24AWG, 27AWG and 30AWG) by using MATLAB program. Knowledge of the electrical resistance of induction heating system is very important to designers working in the high frequency-supplies.

Keywords: Induction Heating, Induction Cooker, Pancake Coil, Twisted-Wire.

I. INTRODUCTION

Heating with electricity has certain advantages such as fast response, accuracy, automatic control and it cannot be refuted. In electrical heating process high frequency electrical heating is more energy efficient as compared to other power frequency electrical heating for domestic cooking purpose. High rate of heat generation, immediate response, more uniform heat distribution, precise temperature control, full automation, good compactness and high reliability are major features of high frequency electrical heating. High frequency electrical heating are of two types; i.e. dielectric heating and induction heating. For cooking purpose induction cooker is the well-known application of induction heating. These cookers are also easier to clean because the food cannot burn if it drops onto the cooking surface as it is not hot. Induction cooker coils are made of many types of wire such as solid, foil, hollow, litz and twisted.

Simple stranded wire without insulation on the individual strands has recently been proposed as a cost-effective substitute for litz wire for reducing eddy-current loss in high frequency transformer and inductor windings [1]. Although it seems self-evident that the individual copper strands that constitute litz wire should be insulated to prevent circulating currents and to effect the function of litz wire in reducing losses, stranded wire with un-insulated strands, which we will refer to simply as stranded wire, can be expected to reduce circulating currents significantly compared to solid wire. Choosing a litz wire design is difficult, because of the large design space of possible choices for number and diameter of strands. The development of the new high frequency induction heating cooker, boiler and super-heated steamer, that is high performance, high power density and high-efficiency compared with the conventional gas cooking equipment are much more attractive for home and business uses.

II. INDUCTION HEATING

Induction heating is a method of heating conductive objects by means of electromagnetic induction. This method of heating is of great interest to materials and manufacturing industries as it is fast, precise, and controllable. All induction heating (IH) applied systems are developed using electromagnetic induction, 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 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 the secondary circuit located near it [2], [3].

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. Figure 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 unity. 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 1(b). 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.

Because 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.

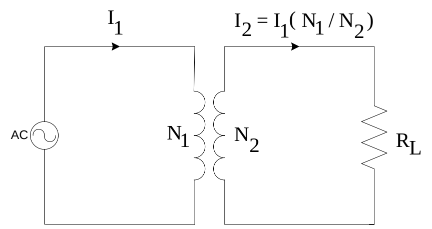

Figure1(a). Equivalent circuit of transformer

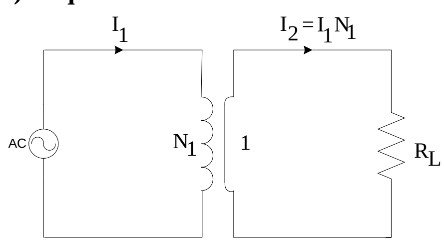

Figure 1(b). Secondary short circuit

III. OPERATION OF INDUCTION COOKER

The induction cooking is one of the many applications for induction heating using high-frequency resonant inverters. It is designed to replace ordinary stove plates. Although induction cooking has high initial cost in comparison with a conventional stove plate, it has many advantages including cleanness, safety, high efficiency, high power density, high reliability, maintainability and controllability [4], [5]. The power of an induction cooker is instantly controllable. This results in quick rise in temperature, which in turn results in reduced cooking times. If the cooking vessel is removed from the cooker, the power is instantly reduced to a minimum.

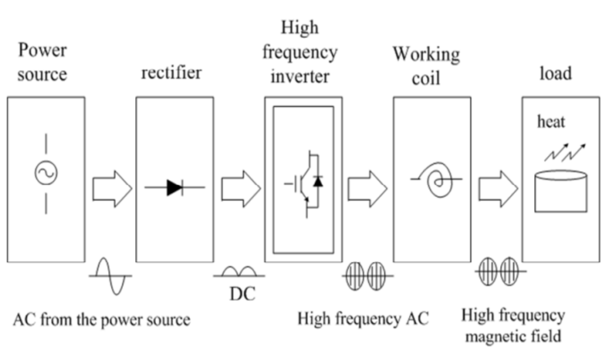

Figure2. Operating Theory of Induction Heating Cooker

This concept can be simplified as follows: First, convert the AC current coming from the power source to DC using a rectifier. Then, connect this DC current to a high-frequency switching circuit to administer high-frequency current to the heating coil. According to Ampere's Law, a high-frequency magnetic field is created around the heated coil. If a conductive object, e.g. the container of a rice cooker, is put inside the magnetic field, the induced voltage and an eddy current are created on the skin depth of the container as a result of the skin effect and Faraday's Law. This generates heat energy on the surface of the container. Food is cooked by using this heat energy.

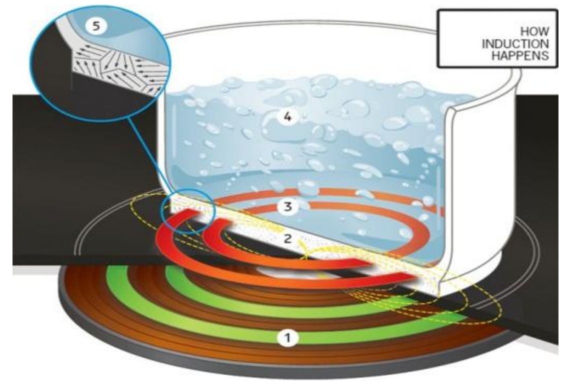

Figure3. Basic principle of electromagnetic induction

1. Electric current

A magnetic field is generated by a 220-volt, 20-to-50 kHz frequency electric current from a 40- or 50-amp breaker through a copper coil.

2. Magnetic field

The magnetic field acts as a bridge, linking the electric current in the copper coils with eddy currents induced in ferromagnetic cookware.

3. Eddy currents

Magnets pull otherwise randomly distributed electrons in a consistent direction. The magnetic field sets the pan's electrons into organized motions known as eddy currents. The currents generate heat in the pan walls.

4. Joule effect

Resistance to electron flow is higher in the cookware than in copper. Increasing the resistance raises the heat.

5. Hysteresis

Hysteresis is important for induction cooking as it is the dominant source of heating. The intermolecular friction and heat made by the IGBT result from a process called hysteresis. Both hysteresis and eddy currents generate heat in the cookware.

IV. DESIGN CONSIDERATION OF HEATING COIL

The design and optimization of heating coil is very important for the analytical analysis of high frequency inverter fed induction cooker. Moreover, accurate prediction of high frequency winding loss is necessary. The eddy current loss includes skin effect loss and proximity effect loss. Brief discussions on two kinds of losses i.e., skin effect loss and proximity effect loss. The skin effect occurs when a sinusoidal current flowing through a conductor and creates a sinusoidal magnetic flux within the conductor which is perpendicular to conductor axis. This magnetic flux produces eddy current which flows in the opposite direction that of the main current flowing through the conductor [6]. Skin depth is normally expressed as

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}} \quad (1)$$

Where, δ = skin depth (m)
μ = magnetic permeability
f = frequency (Hz)
ρ = electrical resistivity of material (Ωm)

Proximity effect occurs due to the generation of magnetic field among the adjacent conductors. In that case proximity effect further divided into internal proximity effect and external proximity effect. Internal proximity effect is the effect of the other current within the bundle and external proximity effect is the effect of current in other bundles.

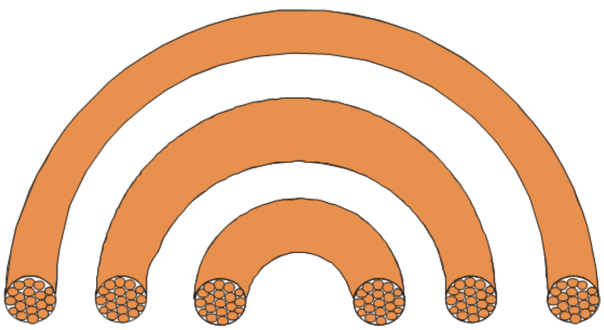

Figure4. Cross-sectional view of pancake coil.

V. CALCULATION OF PANCAKE COIL DESIGN

TABLE I: SPECIFICATIONS OF CONDUCTOR

Specification	Value
Material	Copper
Resistivity (Ωm)	1.7×10^{-8}
Permeability (H/m)	1
Number of strand	19

TABLE II: SPECIFICATIONS OF WORK PIECE

Specification	Value
Material	Carbon steel
Resistivity (Ωm)	12.7×10^{-8}
Permeability (H/m)	1

A. Calculation of Pancake Coil

The number of turns of the coil is mainly based on the diameter of work piece and the spacing between coil windings.

$$N = \frac{r_{out} - r_{in}}{d_{con} + S} \quad (2)$$

Where, N = number of turns of the coil
r_{out} = outer radius of work coil (m)
r_{in} = inner radius of work coil (m)

Overall coil length is calculated as follow.

$$l_c = \pi N (r_{out} + r_{in}) \quad (3)$$

Where, l_c = length of the coil (m)

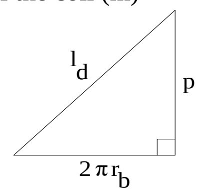

Figure5. Effect of twisting on the length of the strand

$$l_{tot} = l_c \sqrt{1 + \left(\frac{2\pi r_b}{p}\right)^2} \quad (4)$$

Where, l_d = the nominal length of the twisted strand per turn (m)
p = pitch
r_b = bundle radius of the conductor (mm)
l_{tot} = the total untwisted length of a strand (m)

$$d_b = d_b^u \sqrt{1 + \frac{\pi^2 n d_s^2}{4K_a p^2}} \quad (5)$$

Where, d_b = bundle diameter of the work coil (mm)
d_b^u = bundle diameter without twisting (mm)
d_s = diameter of the strand (mm)
K_a = packing factor
n = number of strands

B. Calculation of Operating Frequency

The maximum frequency can be approximately estimated at the characteristic point of individual strand where the skin depth is equal to the radius of strand r_s.

So, at $f = f_{max}$, $r_s = \delta$

$$f_{max} = \frac{\rho}{\pi \mu_0 r_s^2} \quad (6)$$

When the radius of the solid wire or the equivalent bundle wire (r_b) is equal to the skin depth, the frequency is very low.

So, at $f = f_{min}$, $r_b = \delta$

$$f_{min} = \frac{\rho}{\pi \mu_0 r_b^2} \quad (7)$$

The operating frequency should be between f_{min} and f_{max}.

$$f_{op} = \sqrt{f_{min} \cdot f_{max}} \quad (8)$$

C. Calculation of Inductance and Resistance of Work Coil

The inductance of a multiple strand litz wire will be

$$L_{st} = 2 \times 10^{-7} \ln\left(\frac{1}{D_s}\right) \quad (9)$$

$$D_s = \left[(D_{ii})^{19} \left\{ \prod_{i=7}^{19} D_{7,i} \right\} \left\{ \prod_{i=1}^{19} D_{1,i} \right\}^{6} \left\{ \prod_{i=8}^{19} D_{8,i} \right\}^{12} \right]^{\frac{1}{19^2}} \quad (10)$$

Where, L_{st} = the inductance of the coil (H/m)
D_s = the self GMD (m)

$$L_c = \frac{N^2 R^2}{8R + 11W} \quad (11)$$

Where, N = total number of turns

R = mean radius of the coil (in inches)

W = depth of the coil (in inches)

The total inductance of the pancake coil is obtained using the expression mentioned below.

$$L = l_c \times L_{st} + L_c \quad (12)$$

Where, L = total inductance of pancake coil (μH)

L_c= inductance of the coil (μH)

Inductive reactance for work coil (Ω) is

$$X_L = 2\pi f L_c \quad (13)$$

The DC resistance of (R_{dc}) of the twisted bundle is given by

$$R_{dc} = R_{dc}^{u}\left[1+\frac{\pi^2 n\, d_s^{\,2}}{4K_a p^2}\right] \quad (14)$$

Where, R_{dc} = the DC resistance (Ω)

R_{dc}^{u} = the DC resistance without twisting (Ω)

The depth of penetration of the work coil is

$$\delta_c = \sqrt{\frac{\rho}{f\,\pi\,\mu_0}} \quad (15)$$

$$R_c = R_{dc} \times \frac{r_c}{2\delta_c} \quad (16)$$

Where, R_c = the resistance of work coil (Ω)

r_c = radius of conductor (mm)

The optimal value of AC resistance may be obtained using the expression:

$$R_{ac} = \frac{192 R_{dc}^{\,3} + 2\left(8\pi f\times10^{-7}\right)R_{dc}}{192 R_{dc}^{\,2} + \left(8\pi f\times10^{-7}\right)^2} \quad (17)$$

The resistance of the work piece is

$$R_w = \frac{\rho}{\delta} = k\sqrt{\rho\,\mu_r\, f} \quad (18)$$

The magnetizing inductance of the work piece is

$$M = \frac{R_w}{2\,\pi\, f} \quad (19)$$

$$L_{eq} = L_c + M \quad (20)$$

$$R_{eq} = R_c + R_w \quad (21)$$

Where, L_{eq} = equivalent inductance of work coil and work piece (μH)

R_{eq} = equivalent resistance of work coil and work piece (Ω)

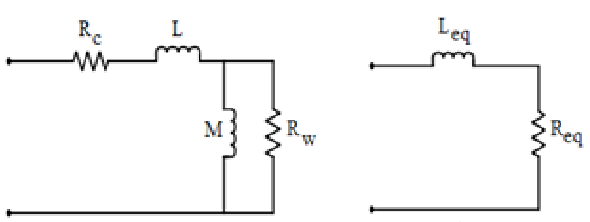

Figure5. Resonant tank circuit of work coil and work piece

VI. RESULTS OF CALCULATED DESIGN

TABLE III: CALCULATED RESULTS FOR WORK COIL AND WORK PIECE

Physical Parameters	Coil Size		
	24AWG	27AWG	30AWG
Number of turns, N (turn)	20	28	40
Length of the coil, l_c (m)	7.1817	10.0544	14.3634
Total length of the conductor, l_{tot} (m)	7.1835	10.0641	14.3643
Bundle diameter of the twisted wire, d_b (mm)	2.5529	1.8035	1.27
Operating frequency, f_{op} (kHz)	13	26	53
Resistance of work coil, R_c (Ω)	0.03462	0.0976	0.2809
AC resistance of work coil, R_{ac} (Ω)	0.042	0.0955	0.25871
Inductance of work coil, L (μH)	49.6928	92.506	180.8024
Equivalent inductance, L_{eq} (μH)	49.70268	92.51299	180.8073
Equivalent resistance, R_{eq} (Ω)	0.0354	0.09814	0.28253
Magnetizing inductance,M (μH)	0.00988	0.00699	0.0049

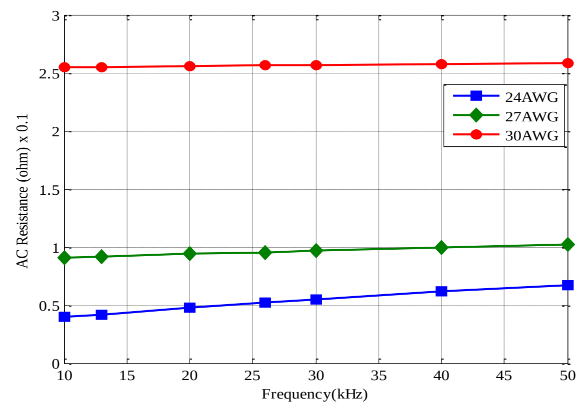

Figure6. AC resistance variation with the operating frequency

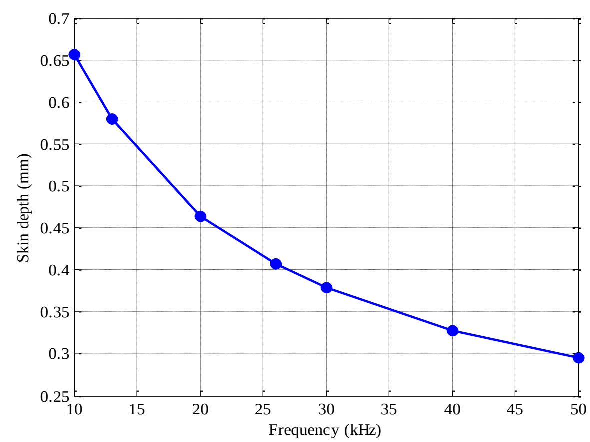

Figure7. Variation of skin depth according to changing of frequency.

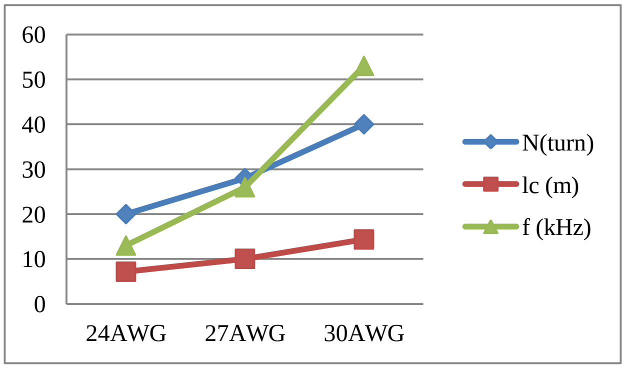

Figure8. Changing the number of turns, length of coil and operating frequency of various coil size.

VII. Conclusion

In this paper, the induction cooker coil with various conductor sizes has been compared. The loss mechanisms due to the skin and proximity effects on a single and multi-strands were derived. It is important to note that inductance of a litz coil increases due to twisting. AC resistances are found to be increasing with the increase in operating frequency. The values of inductance are increasing due to the increasing the number of turns of work coil.

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