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Analysis and Construction of The Multicoil Induction Cookers

A.K.M. Al-Shaikhli, Amanoeel Thomas Mika

Abstract*— Induction cooker is one of the domestic appliances that enjoins increased demand at the present time, because it has proved its efficiency compared to traditional cookers. Some features of the advantage of the induction cooker are speed in heating and good performance in heat distribution. This paper deals with multicoil induction cookers which can be classified into three types. The first type discuss how to heat any kind of metal loads (magnetic or non-magnetic), while the second type discuss how to increase the diameter of the coil (obtain adaptable – diameter burners formed by concentric planar windings). Finally, the third type discuss the effect of two considerations on the characteristic of the control circuit in the double coil induction cooker, the first is the gap length between the load and heating coil, and the second is the kinds of the load.

Index Terms*—Induction cooker, multicoil induction cookers, adaptable – diameter burners, gap length between the load and heating coil , kinds of the load.

I. INTRODUCTION

In common, induction heating is a contactless technique of generating heat energy in a conductive material by producing eddy current losses in the work piece from an external variable high-frequency power source. Over the last ten years, induction cooking is much used, because of its advantages compared to conventional heating systems (resistance, gas, etc...), in particular direct heating of pan without thermal inertia [1]. The induction cookers constitute the most famous domestic application of the induction heating phenomena [2]. In this paper, the types of multicoil induction cookers have been studied. An analytical model to calculate the equivalent impedance of this cooker is presented. There are three types of multicoil induction cookers. First type represented introduction to the use of two coil cooker and the aim of this type is to heat any kind of metal vessels because the first version of induction cooker could not heat the nonmagnetic vessels such as aluminum. The second type is the adaptable – diameter coil which is used to increase the range of suitable pot's diameters and to achieve a better use of the installed power electronics. Such inductors are arranged by means of several concentric planar windings, usually up to two or three units. The use of concentric multiple-winding inductors has clear benefits: a given burner can operate with a wider range of pots and higher maximum power when only one of the windings is active. The third type is double coil system represent superb new technique. This type very essential to estimate the heating coil inductance in safeguarding the stable soft switching operation and the ability of soft switching operation through the calculation of circuit constants in double coil system. A practical double coil induction cooker was constructed to find the effect of the (a) gap length between the load and heating coil and (b) kinds of the loads on the characteristic of the double coil system.

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***Correspondence Author(s)**
Prof. Dr. A. K. M. Al-Shaikhli, Department of Electrical Engineering, University of Technology, Baghdad, Iraq.
Amanoeel Thomas Meka, Department of Electrical Engineering, University of Technology, Baghdad, Iraq.

II. ANALYSIS AND MODELING OF MULTICOIL INDUCTION COOKERS

First Type

In this cooker the coil turns used for nonmagnetic vessels are different from those for magnetic vessels. The coil consist of double layers, as shown in Figure (1), 50 turns in the upper layer and 15 turns in the lower layer. For heating nonmagnetic vessels, the upper and the lower coils are connected in series. For magnetic vessels, the lower coil is used alone. The magnetic field near the exciting coil when heating nonmagnetic vessels is much stronger than when heating magnetic vessels [3].

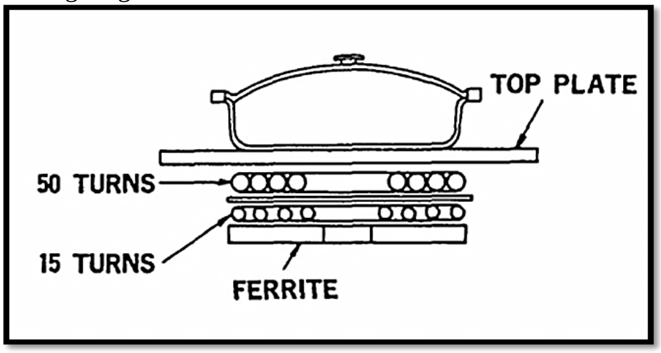

Figure (1) : Exciting Coils Applicable to Any Kind of Metal Vessels

The resistance of metal vessels is dependent on resistivity, magnetic permeability and frequency because of the phenomenon of the skin effect. The skin depth is given by:

$$\delta = \sqrt{\frac{1}{4\,\pi^2 \times 10^{-7}}}\;\sqrt{\frac{\rho}{f \cdot \mu_r}} \qquad (1)$$

Where ρ *: resistivity (Ω.m)*
f *: frequency (Hz)*
μ_r*: relative magnetic permeability*

The exciting coil and the vessel can be regarded as a transformer .The primary coil has the same number of turns as the exciting coil. The secondary coil has a single turn and its load (R_L). The input resistance of the coil can be approximately evaluated by the following formula:

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$$R_{in} \propto N^2.R_s \quad (2)$$

$$R_s = \frac{\rho}{\delta} = \sqrt{4\pi^2 \times 10^{-7}}\sqrt{f.\mu_r.\rho} \quad (3)$$

Where R_{in} *input resistance of the coil (Ω) .*

Rs *: surface resistivity (Ω)*

N*: number of turns of coil.*

Substanding equation (3) in (2) , we get

$$R_{in} \propto N^2.\sqrt{4\pi^2 \times 10^{-7}}\sqrt{f.\mu_r.\rho} \quad (4)$$

The vessel resistance (R_L), is proportional to the surface resistivity Rs of the vessel material, and can be written as :

$$R_L = \frac{\rho}{\delta} = \sqrt{4\pi^2 \times 10^{-7}}\sqrt{f.\mu_r.\rho} \quad (5)$$

To calculate the equivalent impedance of the system, use the relationships of ideal transformer to get :

$$Zeq = \sqrt{4\pi^2 \times 10^{-7}}\sqrt{f.\mu_r.\rho} * N_1^2 \quad (6)$$

Second Type

Recently, some improvements are being developed and applied to the induction cookers. Two or more concentric windings, each one of them fed by an inverter (see Figure (2)), forming a large-size burner, are being implemented. The activation of the windings is planned according to the diameter of the pot [4].

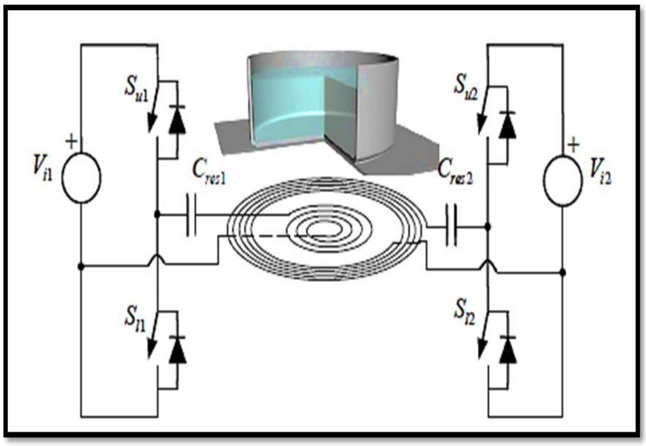

Figure (2) : Schematic representation of a burner consisting of two concentric windings each one of them supplied by a resonant half-bridge inverter

The modeling of the coupled inductor-pan system has often been dealt by means of the transformer analogy. This approach is also suitable to characterize the system in terms of the matrix impedance. In the classical case shown in Figure (3), the voltages of the sources can be expressed as:

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \quad (7)$$

The term Zij corresponds to the impedance of a single i^{th} winding placed between two media, one of them representing the pot and the other the ferrite which usually is placed to improve the coupling [4].

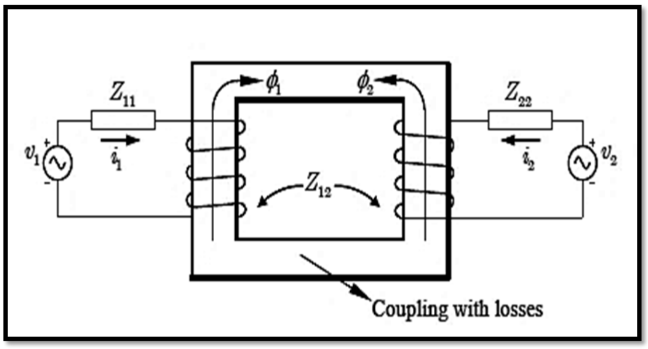

Figure (3) : Basic structure of a transformer used for modeling an induction system consisting of two concentric planar windings sharing the same pot

The impedance corresponds to the series connection of equivalent resistor and inductor is:

$$Z_{ii} = R_{eq,ii} + jwL_{eq,ii} \quad (8)$$

Moreover, both $R_{eq,ii}$, $L_{eq,ii}$ can be expressed as the sum of the contribution of the winding and the media:

$$R_{eq,ii} = R_{o,ii} + \Delta R_{ii} \quad , \quad L_{eq,ii} = L_{o,ii} + \Delta L_{ii} \quad (9)$$

Where

$R_{o,ii}$: represents the losses in the cables of the i^{th} winding.

ΔR_{ii}: is a resistance associated to the inductive heating of the media.

$L_{o,ii}$: is the self-inductance of the i^{th} winding.

ΔL_{ii} : represents the contribution of the media.

The terms Z_{ij} are obtained by evaluating the derivative of the flux of the magnetic induction B over the j^{th} winding. The z component of the magnetic field generated by a circular filamentary current of radius a_{im} (belonging to the i^{th} winding) at any point (r , z) such as $0 < z < d_1$ is

$$H_{z,a_{im}}(r,z) = a_{im}\frac{I_{\phi,i}}{2}\int_0^\infty \beta e^{-\beta z}\left(1+\phi_1 e^{2\beta(z-d_1)}\right)\times \frac{(1+\phi_4 e^{2\beta(z-d_1)})}{(1-\phi_1\phi_4 e^{2\beta(d_1+d_2)})} J_1(\beta a_{im}) J_o(\beta r)\, d\beta \quad (10)$$

Where

β is the integration variable of the Fourier-Bessel transform

J_o is the Bessel function of first kind and order 0

J_1 is the Bessel function of first kind and order 1

$$\phi_1(k) = \frac{k\,\mu_{r1}+\eta_1}{k\mu_1-\eta_1} \quad (11)$$

$$\phi_4(k) = \frac{k\,\mu_{r4}+\eta_4}{k\mu_4-\eta_4} \quad (12)$$

Parameters ϕ_1 and ϕ_4 depend on the integration variable k , frequency and properties of the material.

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$$\eta_1 = \sqrt{k^2 + j\omega\, \mu_{r1}\, \mu_o\, \sigma_1} \tag{13}$$

$$\eta_4 = \sqrt{k^2 + j\omega\, \mu_{r4}\, \mu_o\, \sigma_4} \tag{14}$$

Parameters η_1 and η_4 are complex and dependent on frequency and material properties.

$$k = \sqrt{\mu\omega\sigma} = \frac{\sqrt{2}}{\delta} \tag{15}$$

$$\delta = \sqrt{\frac{2}{\mu\,\omega\,\sigma}} \tag{16}$$

Where
σ : conductivity of the object
μ: permeability of the object
ω :angular frequency of the current flowing through the object

Let $\Phi_{a_{jk},a_{im}}$ be the flux of $B_z\,(r,z)$ generated by the current at a_{im} through the surface limited by the turn placed at $(r = a_{jk}\,, z = 0)$, belonging to the j^{th} winding. This flux is calculated by means of

$$\Phi_{a_{jk},a_{im}} = \iint Bz\,ds = \mu_o \int_0^{2\pi}\int_0^{a_{jk}} H_z\,(r,z=0)\,r\,dr\,d\phi \tag{17}$$

Applying the superposition principle, the total flux through the turn placed a $r = a_{jk}$, $\Phi_{a_{jk}}$ is obtained by adding the flux created by the rest of the turns of the i^{th} winding.

Moreover, the global flux through the j^{th} winding , Φ_{ij} is obtained by summing the flux of every k^{th} turn, i.e.

$$\Phi_{ij} = \sum_{k=1}^{n_j} \Phi_{a_{jk}} = \sum_{k=1}^{n_j}\sum_{m=1}^{n_i} \Phi_{a_{jk},a_{im}} \tag{18}$$

Using (10) and (18) the global flux results

$$\Phi_{ij} = I_{\phi,i}\,\pi\mu_o \int_0^{\infty} \frac{(1+\phi_1 e^{-2\beta d_1})(1+\phi_4 e^{-2\beta d_4})}{(1-\phi_1\phi_4 e^{-2\beta(d_1+d_4)})}\; G\,(\beta, a_{im}, a_{jk})\,d\beta \tag{19}$$

Where $G\,(\beta, a_{im}, a_{jk})$ is a function depending on the geometry and the number of turns of the windings and defined as [5].

$$G\,(\beta, a_{im}, a_{jk}) = \sum_{k=1}^{n_j}\sum_{m=1}^{n_i} a_{im}\; J_1\,(\beta\, a_{im})\, a_{jk}\, J_1\,(\beta\, a_{jk}) \tag{20}$$

$$Z_{ij} = \underbrace{j\omega\pi\mu o \int_0^{\infty} G(\beta, aim, ajk)\,d\beta}_{zo,ij} + \underbrace{j\omega\pi\mu o \int_0^{\infty} \frac{\emptyset_1 e^{-2\beta d1} + \emptyset_4 e^{-2\beta d2} + 2\,\emptyset_1\emptyset_4 e^{-2\beta(d1+d2)}}{(1-\emptyset_1\emptyset_4 e^{-2\beta(d1+d2)})} G(\beta, aim, ajk)\,d\beta}_{\Delta Zij} \tag{21}$$

$$\Delta R_{ij} = Re\,[\Delta Z_{ij}]\,;\quad \Delta L_{ij} = \mathrm{Im}\,[\Delta Z_{ij}/\omega]$$

(22)

Third Type

This type studies possibility of soft switching operation through the calculation of the circuit constants in the double coil induction cooker, which had been proposed by us. Figure (4) shows the model of the constructed double coil induction cooker. A double coil is arranged under a metal load. If two currents with different phase of 180 degree are flowed in each of two coils, magnetic field of twice the supply frequency can be generated. Eddy current is induced within a metal whose frequency corresponds to the magnetic frequency. Capacitor C_S connected in parallel with the coil is adopted for the resonance to realize zero volt switching (ZVS) [6].

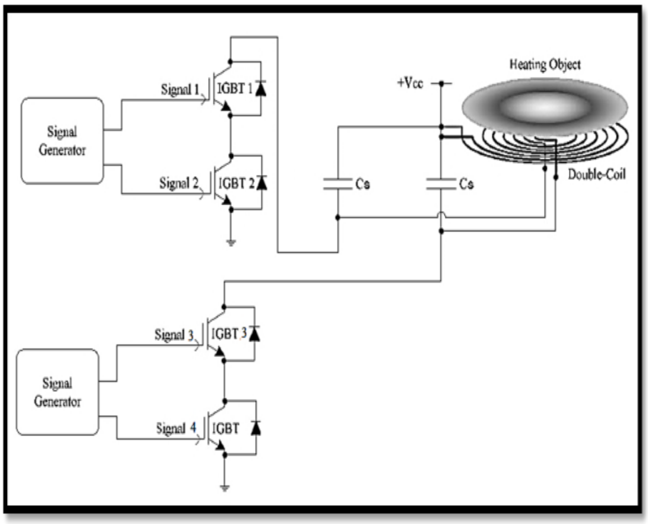

Figure (4) : System Model

Figure (5) shows the model of the designed double-coil. Two coils are arranged in the same plane. These two coils are energetic by the currents, only whose phase is different 180 degrees. In this scheme the frequency of the eddy current induced in the pan is increased. Using this system, high frequency eddy current which reaches 2 times that of switching frequency can be induced within a pan. Depending upon the generation of high frequency eddy current, skin effect of the heating object becomes amazing. Heating of non-magnetic material , which cannot be heated up to now, becomes possible [6].

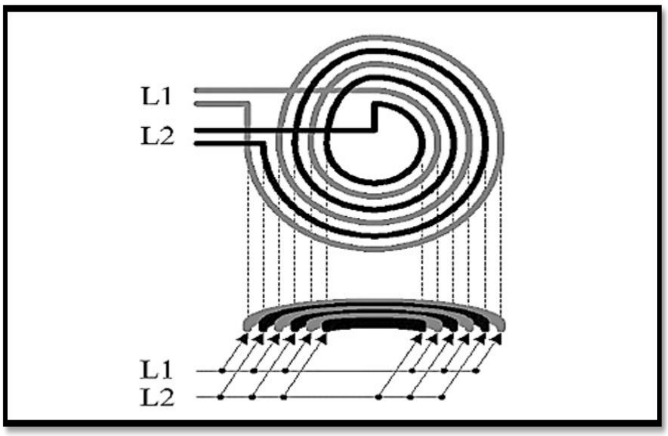

Figure (5) : Model of Double-Coil

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Equivalent circuit of double coil system is shown in Figure (6). From this Figure noted the double coil system converted into three-coil transformer. Primary side represents the heating coil and consists of two coils and secondary side represents the load. When the gap length between heating coil and metal load changes, equivalent impedance looked from the primary side of the transformer also changes because the combination coefficients between three coils change. Therefore, resonant frequency changes, because it is determined by the value of the capacitor C_s introduced for the sake of soft switching and equivalent circuit inductance [7].

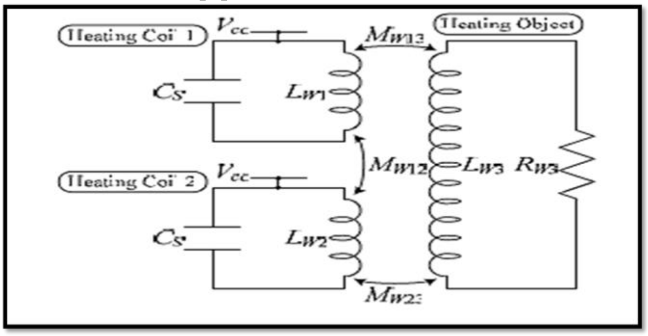

Figure (6) : Equivalent Circuit of Double-Coil System

III. Practical Design of Double Coil Induction Cooker and Experimental Method

The simulation and practical circuit of double coil induction cooker shown in Figure (7 (a&b)) respectively. The design consist of mainly two circuit (power supply circuit and control circuit) and the heating coils.

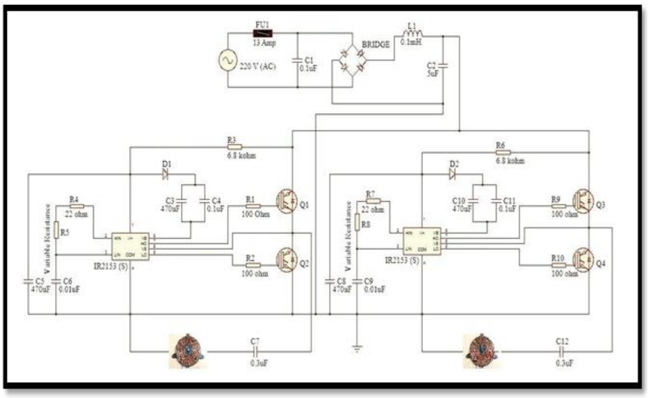

Figure (7 (a)) : Simulation Circuit of Double Coil Induction Cooker

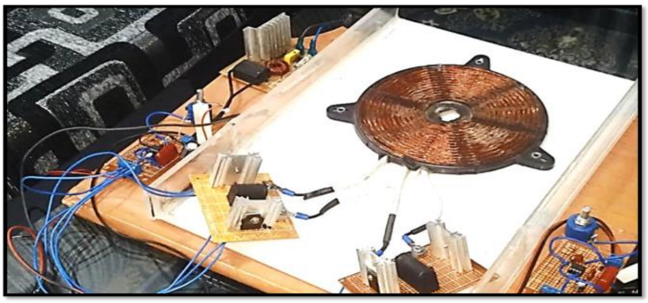

Figure (7 (b)) : Practical Circuit of Double Coil Induction Cooker

Power Supply Circuit : This circuit connected the rectifier component to convert the (AC) to (DC). Figure (8 (a&b)) show all components used in the power supply circuit.

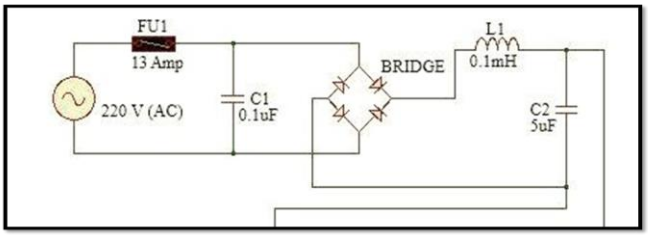

Figure (8 (a)) : Simulation Power Supply Circuit

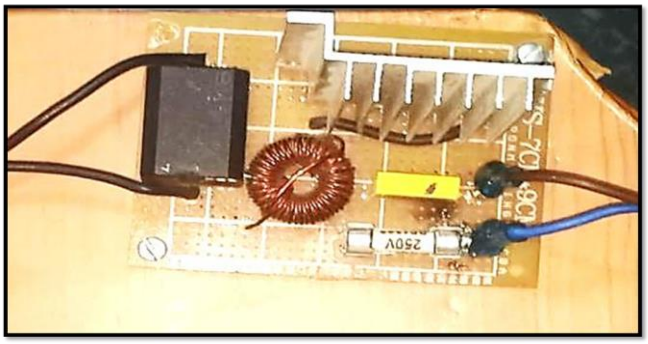

Figure (8 (b)) : Practical Power Supply Circuit

Control Circuit : there are two control circuit connected in this design because it is a double coil induction cooker, which need two control circuit each circuit controls one coil. Figure (9 (a&b)) shows all components used in the control circuit.

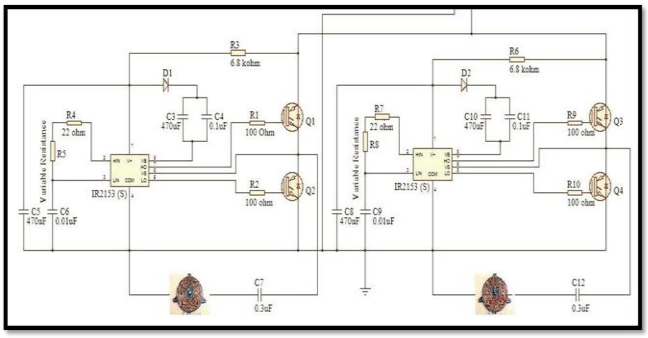

Figure (9 (a)) : Simulation Control Circuit

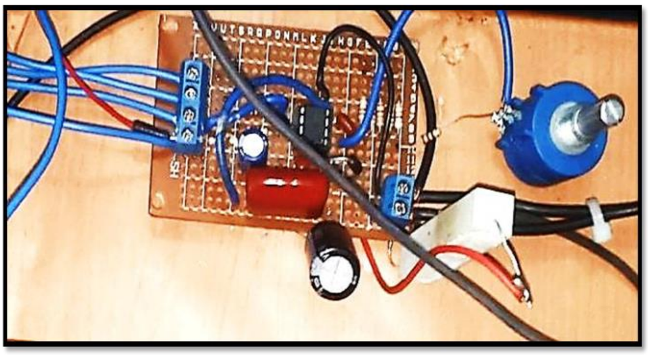

Figure (9 (b)) : Practical Control Circuit

Controller (IR2153(S)) is an improved version of the popular IR2155 and IR2151 gate driver ICs, and joins a high voltage half-bridge gate driver with a front end oscillator similar to the 555 timer IC. The IR2153 offers more functionality and is easier to use than previous ICs. Figure (10) shows typical connection of (IR2153(S)).

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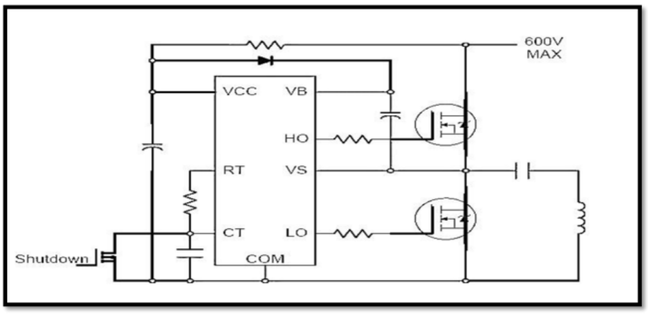

Figure (10) : Typical Connection of (IR2153(S)) Controller

IR2153(S) controller used for generating the pulses that are running IGBT, also made the two IGBT in the control circuit operate synchronously when one IGBT is ON the other is OFF and vice versa. Figure (11) shows input/output timing diagram of two IGBT.

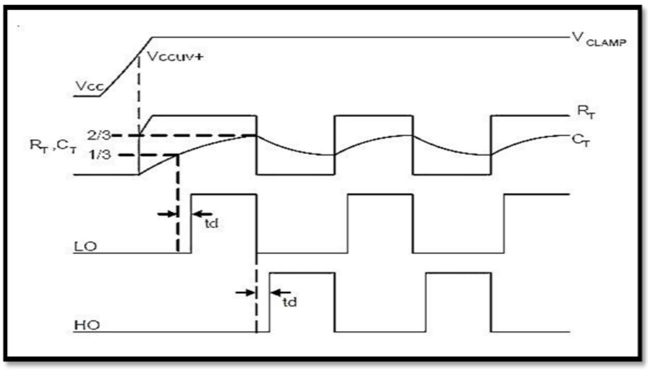

Figure (11) : Input / Output Timing Diagram

Experiment Method :

In this part the setup of the double coil induction cooker is presented. To operate the double coil induction cooker correctly each coil should be supplied by frequency between (20kHz) to (100kHz), select the duty ratio is equal 25% and the phase shift between two supplies is 180 degree. The steps of measuring the equivalent impedance of double coil induction cooker are:

1- The range of frequency taken is from (0.1) kHz to (100) kHz, remaining the output voltage of the oscillator constant.
2- For each value of frequency, the coil inductance was measured, using (L-C) meter. The distance between heating coil and vessel increased by (2mm) started from (0mm) and finished at (20mm).
3- Calculate the coil reactance $X_L = 2\pi f L$, and ignored the resistor of coil because it's very small i.e. the equivalent impedance is equal to the reactance of the coil.
4- The experiment was done for magnetic and in non-magnetic loads. The thickness of the pot used in the experiment is equal to (1mm), circle in shape and have diameter equal to (200mm).

IV. Simulation and Results

There are three types of multicoil induction cookers. The effect of certain parameters on the equivalent impedance was studied. The calculations were carried out in two states: first, the equivalent impedance is calculated without load and the second with load. This comparison helps very much in obtaining the best technical information about cooker coil. The proposed design program is written as an M file using MATLAB programming language (version R2013 a).

First Type

The following results represent the relationship between the equivalent impedance of the first type multicoil induction cooker against frequency. The range of frequency was from 1 kHz to 100 kHz. In this type there are two coils upper and lower. If the cooker is loaded with a magnetic load the lower coil only is operating, when the cooker is loaded with a non-magnetic load both coils are operating. Figures (12) and (13) show the performance of equivalent impedance if the number of turns of upper coil equal the number of turns of the lower coil, but in Figure (12) the cooker loaded by magnetic load and Figure (13) the cooker loaded by non-magnetic load. When the cooker loaded with magnetic load, the lower coil is used alone, i.e. in this case the cooker works as a single coil cooker. This kind of cookers work in two way, as a single coil if loaded with magnetic load and as a multicoil when loaded with non-magnetic load. For this reason, this type can be considered as an intermediate case between single coil induction cooker and multicoil induction cooker. Figures (14) and (15) show the upper and lower coils with different number of turns. Figure (14) when the cooker is loaded with magnetic load and Figure (15) when the cooker is loaded with non-magnetic load.

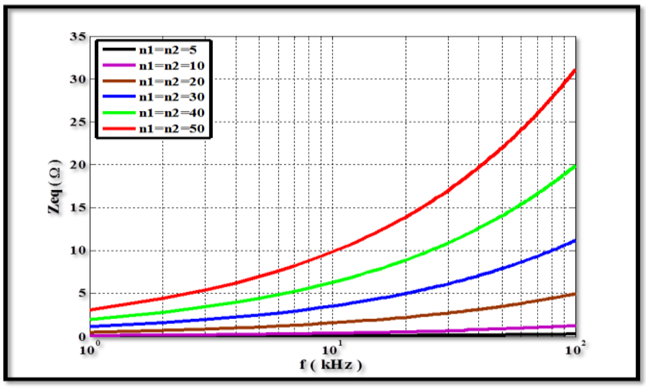

Figure (12) : Equivalent impedance with the same number of turns in upper and lower coils when cooker loaded by magnetic load

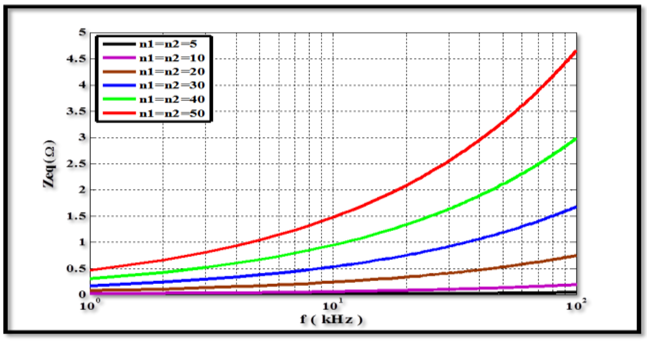

Figure (13) : Equivalent impedance with the same number of turns in upper and lower coils when cooker loaded by non-magnetic load

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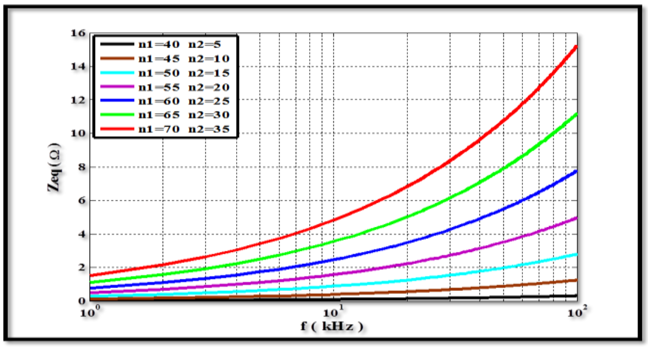

Figure (14) : Equivalent impedance with different number of turns of coils when cooker loaded with magnetic load

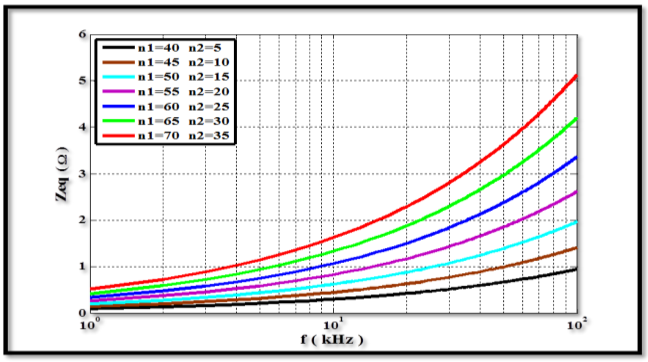

Figure (15) : Equivalent impedance with different number of turns of coils when cooker loaded with non-magnetic load

The type of load changed three times as shown in Figures (16-19) respectively. In Figure (16) and (17) a plot of the equivalent impedance is presented , being the resistivity (ρ) in figure (16) is constant with value equal to $9.8 * 10^{-8}$ to represent the magnetic load with different permeability's with the value of resistivity (ρ) in figure (17) is constant at $2.8 * 10^{-8}$ to represent the magnetic load with different permeability's. Figures (18) and (19) are inverse of Figures (16) and (17) in which the relative permeability (μ_r) in figure (18) is constant of value equal (100) to represent the magnetic load with different resistivity's while the value of relative permeability (μ_r) in figure (19) is constant and equal (1) to represent the non-magnetic load with different resistivity's. All these results correspond to the number of turns of upper coil of 50 turns and lower coil of 15 turns.

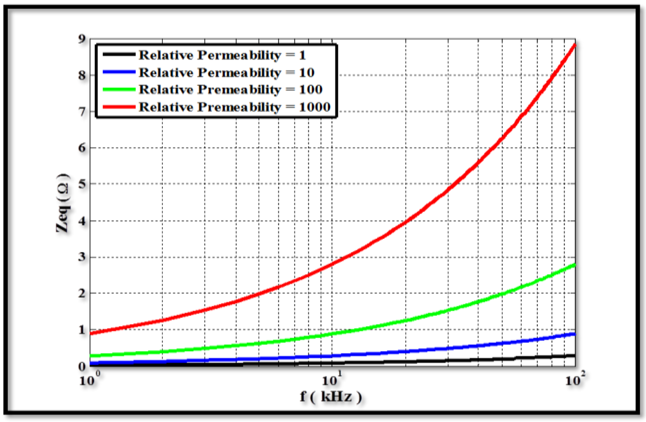

Figure (16) : Equivelent impedance loaded with different permeability's at resisitivity equal $9.8 * 10^{-8}$

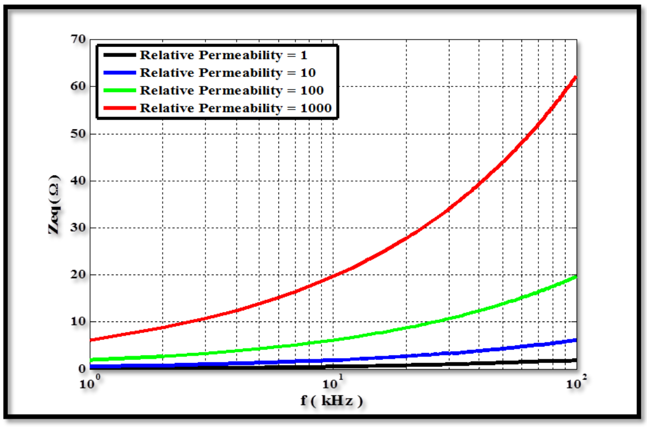

Figure (17) : Equivelent impedance loaded with different permeability's at resisitivity equal $2.8 * 10^{-8}$

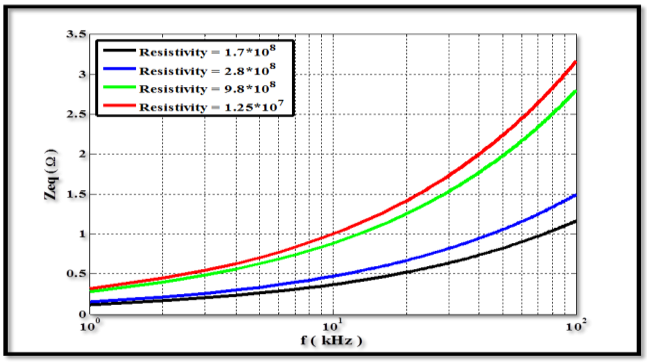

Figure (18) : Equivelent impedance loaded with different resistivity's at relative permeability equal 100

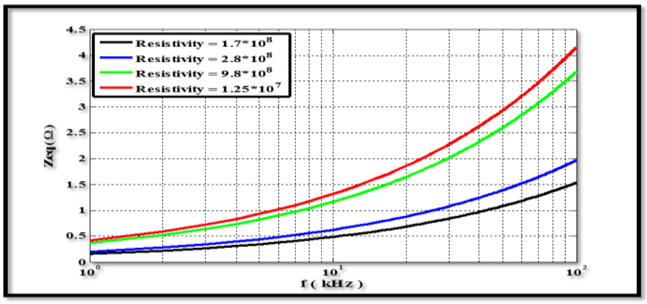

Figure (19) : Equivelent impedance loaded with different resistivity's at relative permeability equal 1

Second Type

The following results represent the relationship between the equivalent impedance of the second type multicoil induction cooker against frequency. The studied frequency range is comprised between (1) kHz and (1) MHz. The equivalent impedance was studied in two cases :

Case (1) : changing the number of turns of first coil and second coil.

Case (2) : changing the internal and external radii of coils.

In first case the number of turns of first and second coil are changed to study the effect of this change on the equivalent impedance of the induction cooker and its constituent quantities. Table (1) show the parameters remain constant with changing the number turns of first and second coil.

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Table (1 (a)) : Input Data of Coils of First Case

Input Data of Coils			
Parameter	**Symbol**	**First Coil**	**Second Coil**
Number of Turns	n	17	9
		12	5
		7	4
		5	3
		3	2
		1	1
Resistivity	ρ	$1.72 * 10^{-8} \Omega$	$1.72 * 10^{-8} \Omega$
Relative Permeability	μ_r	1	1
Internal Radius	$a_{internal}$	$a_{1,int}$ 25 (mm)	$a_{2,int}$ 100 (mm)
External Radius	$a_{external}$	$a_{1,ext}$ 90 (mm)	$a_{2,ext}$ 137 (mm)
Number of Strand	n_s	38	38
Radius of Strand	r_s	0.3 (mm)	0.3 (mm)

Table (1 (b)) : Load Properties of First Case

Load Properties			
Parameter	**Symbol**	**Region 1**	**Region 2**
Relative Permeability	μ_r	150	Complex Permeability
Conductivity	σ	$8 * 10^6$	0.2 $(\Omega.m)^{-1}$

Figures (20-23) show that the R_o and L_o will change direct with changing the number of turns of induction cooker. At the same time ΔR and ΔL change exponentially with the frequency, So the equivalent resistance and inductance of induction cooker (Req and Leq) will be as shown in Figures (21) and (23). From Figures (24) and (25), it can observe that the impedance response in both cases (Non-loaded and loaded) are like those of resistance in Figures (20) and (22) because the small value of inductance at two cases (loaded and non-loaded), which leads to the loaded impedance equal to the loaded resistance and the same thing applies in (non-loaded) case. The results of resistance and impedance show that the value of each one increases at high frequency because both of them are directly proportional to the operating frequency. This increase is generating from the high inductive reactance as a result in high frequency. From the above it is clear that the equivalent impedance increases with the number of turns.

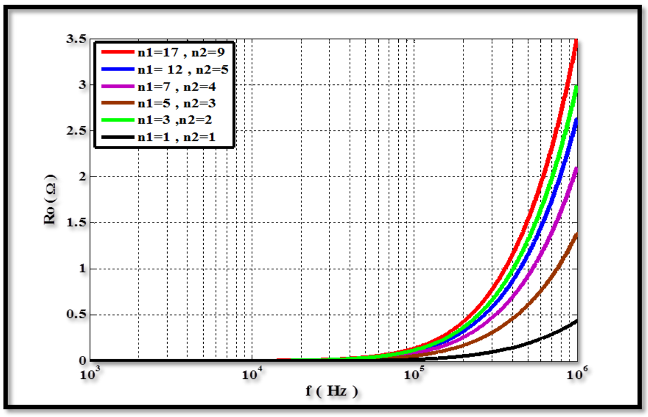

Figure (20) : Resistance of non-loaded winding with different number of turns

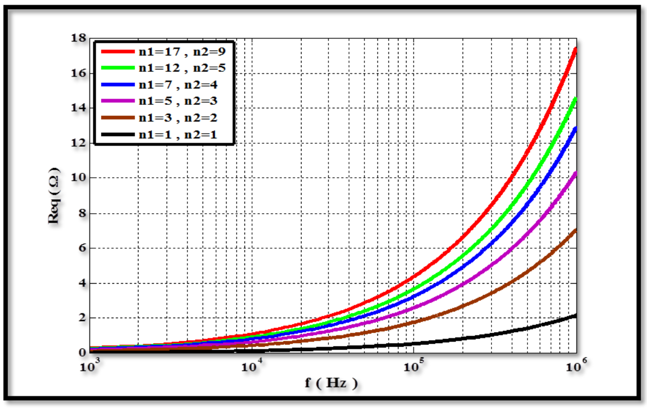

Figure (21) : Resistance of loaded winding with different number of turns

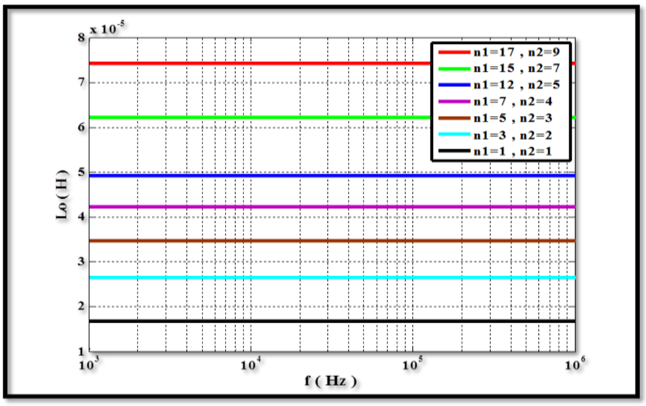

Figure (22) : Inductance of non-loaded winding with different number of turns

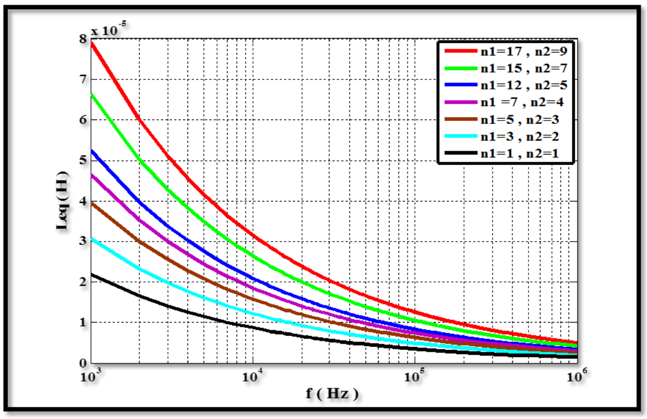

Figure (23) : Inductance of loaded winding with different number of turns

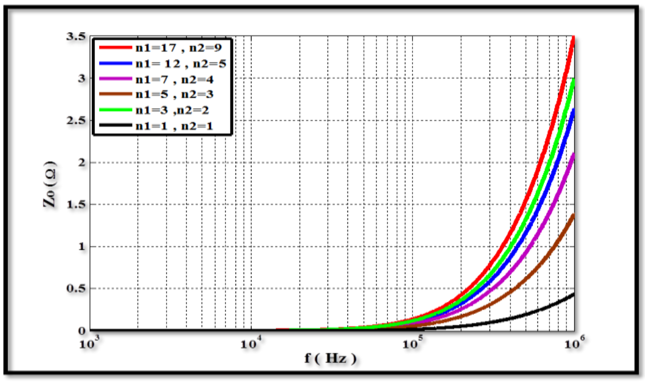

Figure (25) : Impedance of loaded winding with different number of turns

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In the second case the impedance of induction cooker varies with the change of the internal radius of the first coil. Table (2) shows the parameters which remain constant with changing the internal radius of first coil such as number of turns of the coil and the load properties. Changing the internal radius of first coil $(a_{1,int})$ led to change the external radius of this coil and change internal and external of second coil, i.e. changing the internal radius of first coil$(a_{1,int})$ cause changing all radii in the same coil and other coil respectively

Table (2 (a)) : Input Data of Coils of Second Case

Input Data of Coils			
Parameter	**Symbol**	**First Coil**	**Second Coil**
Number of Turns	n	17	9
Resistivity	ρ	$1.72 * 10^{-8}\Omega$	$1.72 * 10^{-8}\Omega$
Relative Permeability	μ_r	1	1
Internal Radius	$a_{internal}$	$a_{1,int}$	$a_{2,int}$
		22 (mm) 25 (mm) 33 (mm) 36 (mm)	97 (mm) 100 (mm) 107 (mm) 111 (mm)
External Radius	$a_{external}$	$a_{1,ext}$	$a_{2,ext}$
		87 (mm) 90 (mm) 97 (mm) 101 (mm)	134 (mm) 137 (mm) 144 (mm) 148 (mm)

Table (2 (b)) : Load Properties of Second Case

Load Properties			
Parameter	**Symbol**	**Region (1)**	**Region (2)**
Relative Permeability	μ_r	150	100
Conductivity	σ	$8 * 10^6$	$0.2\ (\Omega.m)^{-1}$

The resistance of the coil (R_o) or non-loaded resistance and equivalent resistance (R_{eq}) of induction cooker are changed with different values of internal radius of first coil $(a_{1,ext})$ as shown in Figures (26) and (27). The increase of the internal radius of first coil has small effect on the non-loaded resistance. The change of the resistance with frequency less than 100kHz is small, but in the range between (100-1000kHz) the response of non-loaded resistance will be rising gradually. In the range of low frequency between (1-10kHz) the value of equivalent resistance approximately constant with different radii and will be increasing at high frequencies. The effect of increasing the internal radius on the non-loaded resistance be a little in most ranges of frequency as shown in Figure (26), while in loaded resistance the change be clear specially in high frequency as shown in Figure (27). Loaded and non-loaded inductance of a coils increases due to twisting. It has also been noticed that the value of inductance increase as the strand dimension increase. It may have happened due to the increase in bundle diameter after twisting and increase length of the spiral coil for keeping effective length to be equal to that of coil before twisting. Figures (28) and (29) show this increasing. Two last Figures (30) and (31), show that the impedance curves are like those of resistance in relation with the frequency where both of them are directly proportional with the operational frequency ,taking into considerations the larger values of impedance. This rise is coming from the high inductive reactance as a result of high frequency. The equivalent impedance of this type affected by two case. First case changing number of turns of coils and second case change the value of internal and external radii. The diversity of turn number and radiuses of induction cooker coil due to change in the magnitude of equivalent impedance directly regardless of the type of load (magnetic or non-magnetic) and all results obtained from second type multicoil induction cooker can prove that.

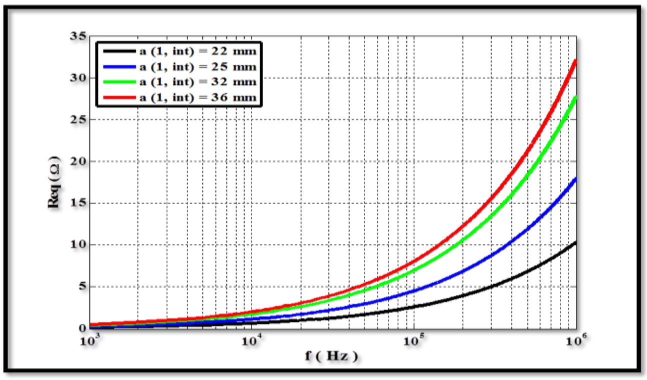

Figure (26) : Resistance of non-loaded winding with different values of internal radius of first coil.

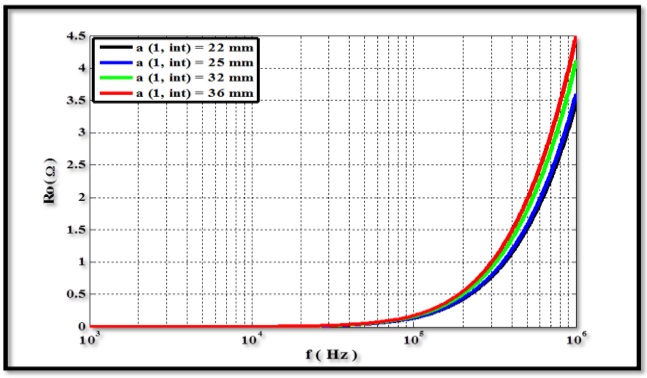

Figure (27) : Resistance of loaded winding with different values of internal radius of first coil.

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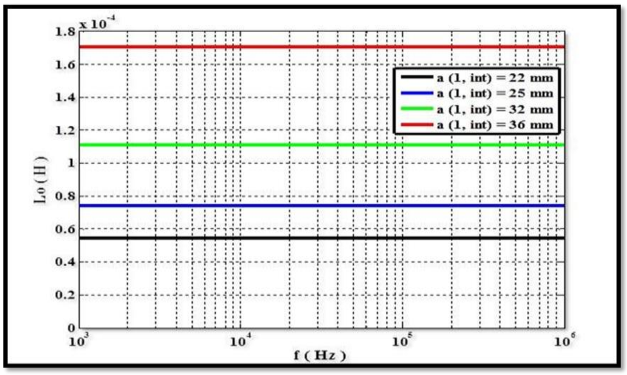

Figure (28) : Inductance of non-loaded winding with different values of internal radius of first coil.

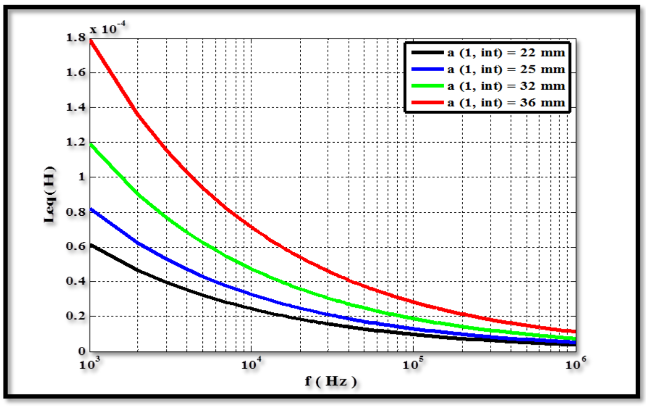

Figure (29) : Inductance of loaded winding with different values of internal radius of first coil

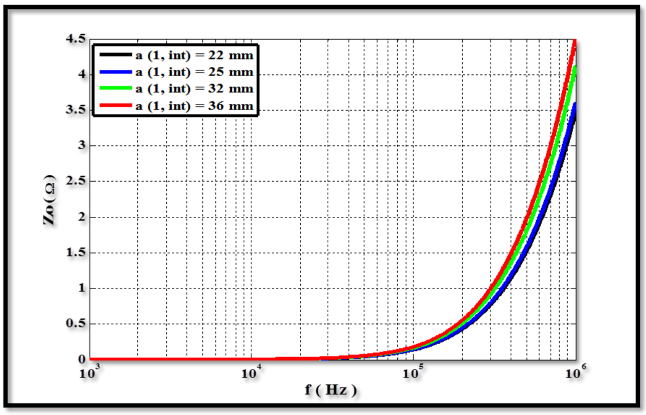

Figure (30) : Impedance of non-loaded winding with different values of internal radius of first coil

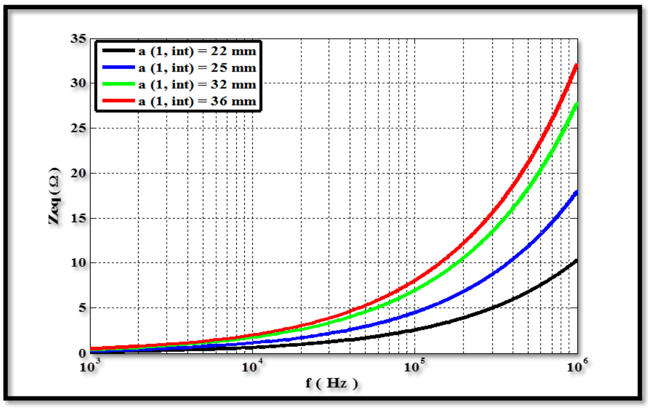

Figure (31) : Impedance of loaded winding with different values of internal radius of first coil

Third Type

In this type, the equivalent impedance performance was studied in two cases. First case changing the distance between heating coil and the load and the second case changing the type of load. All results obtained in this type is experimental results. In this type the equivalent impedance equal to the reactance because the value of the resistance is very small leading to ignored it, In this experiment the values of inductance were measured at the above cases to calculate the equivalent impedance. Figure (32) and (33) show the relationship between the equivalent impedance and frequency with different type of loads (magnetic and non-magnetic), also with values of gap length between heating coil and load. The gap length or distance (d) between heating coil and load (vessel) limited by thickness of ceramic and radius of wire. The thickness of ceramic is taken to be (5 mm) because the range of thickness is between (0.1 mm to 10 mm) does not clearly affect the equivalent impedance, while thickness greater than 10 mm is not practical for induction cooker, and the efficiency became low because the possibility of matching between coil and load decreases.

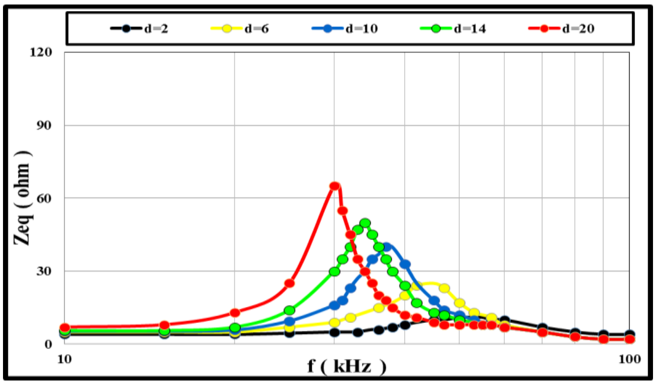

Figure (32) : Equivalent Impedance at Magnetic Load for Different Gap Length

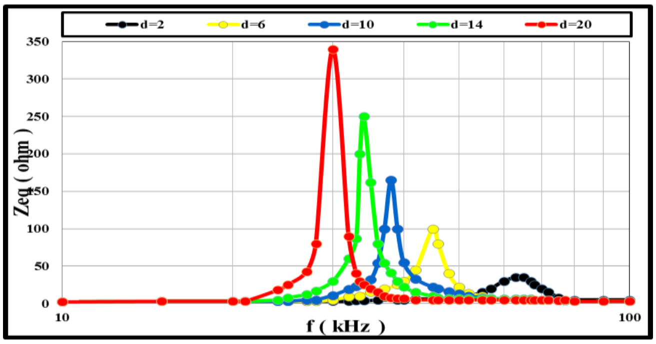

Figure (33) : Equivalent Impedance at Non-Magnetic Load for Different Gap Length

V. Comparison Between Types of Multicoil Induction Cooker

The main aim of this paper is to study the multicoil induction cookers and made comparison between them. There are many factors can be used to compare between these types. The following table shows the comparison between the types of multicoil induction cookers.

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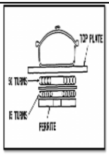
Considerations	First Type	Second Type	Third Type
Real and imaginary terms in equivalent impedance	Contain on real part only	Contain on both real and imaginary parts	Contain on imaginary part only
Effect of increasing number of turns of coils on equivalent impedance	Increase the value of equivalent impedance		
Effect of Type of load material on equivalent impedance	At magnetic load the equivalent impedance more than at non-magnetic load	At magnetic load the equivalent impedance more than at non-magnetic load	At magnetic load the equivalent impedance less than at non-magnetic load
Operating frequency	1-100 (kHz)	1kHz-1MHz	10-100 (kHz)
Connection of the coils			

VI. CONCLUSION

An analytical equivalent impedance models of three kinds of multicoil induction cookers has been developed. Each model takes into account several parameters such as the load properties, the frequency, the number of turns of the winding, internal and external radiuses of coils, distance between the heating coil and load and other geometrical parameters. Different winding number of turns , different radii of coils and different loads were tested with different operating frequencies. Performance of multicoil induction cooker better than single coil induction cooker in terms of (capable power, thermal distribution, speed in heating etc…). Each type of multicoil induction cooker has coils differs from the other type in the construction and method of twisted. First type multicoil induction cooker can be considered as an intermediate case between single coil induction cooker and multicoil induction cooker. In (first and second) type multicoil induction cooker, the magnitude of impedance is directly proportional to the increasing of number of turns of the coils. In second type multicoil induction cooker, when increasing the radii of coils, the equivalent impedance increase too. Impedance curves in second type multicoil induction cooker are to a great extent similar to these of resistance because of the large values of resistance compared with inductance values. In third type multicoil induction cooker, increasing the gap length between heating coil and load due to increase the equivalent impedance. In (first and second) type multicoil induction cooker, using magnetic load gives impedance more than using non ferromagnetic so, lower current will be drawn which results lower loses which means high efficiency. And the state reversed in third type.

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