

Design and Construction of the Coreless Induction Furnace

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Abstract

The main task of the present work is to design and construct a coreless induction furnace. Many analytical methods could be applied to induction heating and melting problems. The most suitable method for the present work is equivalent circuit method, a second approach is the superposition method, to check the results of the first method in one step of the design. Prior to the use of these two methods the dimensions of the furnace, the operating frequency and the required power must be determined as a prerequisite.

A design procedure was developed as computer programs, these programs accomplished a general design which can be utilized to design coreless furnaces of variable specifications. Then, a design, meeting certain specification was prepared, taking into consideration the available facilities. Ultimately, the furnace was constructed and the final aim, which is melting the metal, was achieved.

Key words: Induction Heating, coreless furnace, Equivalent circuit method.

1-Introduction

The coreless induction furnace is considered as the most popular type of the induction furnaces because of its suitability for all metal industries[1]. The coreless induction furnace is a simple unit consisting of a helically wound coil surrounding a refractory crucible containing the molten charge and connected to an alternating excitation system[2].

When the coil is excited by an alternating current it produce an axial alternating magnetic field. The variation of magnetic field produces an electric field and eddy currents along paths concentric with the axis. The electromagnetic field attenuates rapidly inside the charge. The depth at which the induced density falls to (1/e) of its surface value is usually referred to as skin depth. The skin depth δ is given by:

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

eddy currents are concentrated at the outer surface of the charge due to skin effect and heat is developed by the conventional ohmic losses. Part of the developed heat is lost to the surrounding medium, and the remaining part is distributed through the mass of the charge by effect of thermal conductivity[3].

The skin effect is also spread in the coil conductor. Moreover, the distribution of the surface current density over the coil is non-uniform, the greatest current density is to be found in the sections of the coil

lying closest to the charge, this phenomena is known as the proximity effect[4]. The induction furnace is, therefore, based on four principles: Electromagnetic induction, skin effect, heat transfer and proximity effect.

2 - Design Steps of the Coreless Induction Furnace

The equivalent circuit method are general methods that can be applied to analysis and design of all induction heating applications, the coreless furnace is certainly one of them. The equivalent circuit method is regarded as general method because this method doesn't determine the dimensions, frequency or the power requirements of the specific application analyzed and designed by this method. On the contrary, the use of equivalent circuit method requires this information as pre-requisite, so to prepare a complete design of the coreless induction furnace, these information are :

- i- design of crucible which include the determination of height to diameter ratio (L_w/D_w), coil diameter to charge diameter D_c/D_w , and the crucible wall thickness[5, 6].
- ii- Frequency selection: The physical specification of the workpiece and its dimension determine the frequency of the power supply for heat process. This frequency must be greater than critical frequency given in the following equation[3]:

$$f_c = \frac{6.45\rho}{\mu D_w^2}$$

- iii- Determination of the required power: the power supply is selected based on power and frequency required for melting process. The required power consists of : the relative power to melt the charge and the heat losses accompanied the melting process[3].

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- iv- Induction coil design: which it consists of number of copper conductor with proper cross-section to satisfy the required cooling[3, 7].
- v- Determination of the required cooling.

A complete study of performance of furnace is performed from the calculation of the equivalent circuit resistances and inductances. The equivalent circuit is shown in fig.1, where[8]:

$$X_g = K_R \frac{D_c^2 - D_w^2}{4L_c}$$

$$Z_w = R_w + jX_w = K_R \frac{\mu_r D_w^2}{4L_c} (q + jp)$$

$$Z_c = R_c + jX_c = K_R \frac{K_r \delta_c D_c}{2L_c} (1 + j)$$

$$X_r = K_R \frac{D_c}{4(0.45 + K_g)}$$

$$\text{Where } K_R = \omega \mu_0 \pi N_c^2$$

This relationship was derived after knowing the reluctance of magnetic field paths[5].

3 - Design Implementation

In accordance with the theoretical basis, three programs were developed, the first program "Required Power" calculates the required power by the charge to be melt and also calculates the thermal efficiency. The second program "Equivalent Circuit" is based on the equivalent circuit method, as previously mentioned. This method is the main design technique used in this work. The second program is supplemented with a subprogram developed to compute the Bessel functions of the dimensionless constant p and q. The third program " Superposition" based on the superposition method was developed to calculate the number of amper-turns required to melt the charge.[5]

flow charts of " Equivalent Circuit" and " Superposition" program are shown in figs. 2 and 3.

3.1 Preliminary preparation

A variety of the metal were studied to choose the charge. The best furnace capacity obtained was 400 mg because of limited facilities available and the lack of step-down transformer and improper workshop. The most proper charge metal was tin.

3.2 optimizing the crucible dimensions

The dimensions of the designed crucible are given in table 1, depending on the optimum values of the height to diameter ratio (L_w/D_w), coil diameter to charge diameter D_c/D_w , and the crucible wall thickness

3.3 Design of the power supply

The critical frequency, for the furnace to be construct in this work is equal $f_c = 462$ Hz, so the use of the main-frequency power supply is not possible. The power supply circuit is made up of three parts including rectifier, chopper, and load circuit, a complete circuit diagram of the power supply is shown in fig. 4. The three phase input voltage is converted to DC voltage by means of three phase rectifier. The DC voltage is chopped using MOSFET with an external oscillator in the firing circuit to give the desired frequency. The load circuit is a resonant circuit consisting of the induction coil and the load matching capacitor. The power control is obtained by varying the three phase voltage by using a three phase transformer.

4 - Construction steps of the furnace

4.1 Construction

The material used to construct the crucible was fireclay. This material have very acceptable thermal, mechanical, metallurgical qualities for the task, also there is available experience in handling this material.

An iron mold was designed and constructed, consisting of three parts; a male, female to demarcate the shape of the crucible, and pusher to press the fireclay within the mold between the first two parts.

Then the shapen fireclay was extracted from the mold. After that, it was fired in furnace of about 1600C for 14 hours. The mold and its cross-section view are shown in fig. 5 and 6. Cross-section view of obtained crucible is shown in fig. 7.

4.2 Construction of the induction coil

Neither the equivalent circuit method nor the superposition method specify the number of turns of the induction coil, these method can only obtain amper-turn required by charge to be melt. Figures 8 and 9 shows the amper-turn, versus frequency for equivalent circuit method and the superposition methods respectively.

From the fig.s 8 and 9, it was obvious that the result of the first method are higher than the second method, with difference up to 12.5%. the result of superposition is neglected and the amper-turn result of equivalent circuit method was chosen for a safer option .

Since the designed power supply of this work doesn't have the ability to produce high current, so it was compensated by using a coil of large number of turns of small diameter tube.

The wounded induction coil consists of 16 turns of a copper tube of 3mm diameter. The tube insulated by means of sleeve insulator. Cross-section view of the insulated tube is shown in fig. 10. To fix the turns of coil, an adhesive tape was used, in two layers internal and external.

5 - Operating and Test the furnace

The charge used to test the furnace was 300 gm. of tin. During each test of the charge melting, the frequency was fixed. Also other test with different frequencies were performed. The charge only melted when the frequency used was 12 KHz or more. The raise of temperature of charge during one of melting test was shown in fig. 11.

Many measurements were done during furnace operation in order to estimate the performance and also to compare the practical measurements with theoretical calculations, so the accuracy of the furnace is obtained. Figure 12 represent the impedance of furnace theoretically calculated and practically measured using LCZ meter (type HP4267A). Table 2 illustrate the function efficiency obtained theoretically and measured practically for tests the charge melted successfully.

The required number of amper-turns to melt the charge practically measured and theoretically calculated, is illustrated in table 3.

It is clearly that the increasing of the power and frequency lead to efficiency increasing and decreasing melting time as a result of increasing number of amper-turns.

6 – Conclusion

The charge melting successfully during the tests of furnace operation shows that the design procedure(equivalent circuit method paired with theoretical and practical process) was suitable for such work.

From the study of the tables, figures, theoretical calculations and practical results, It can be notice the coinciding or difference between theoretical values and measurement instrument reading in fig.11. If the reading of (LCZ meter) in fig. 11 considered the reference, then it can be said that the calculation method used gave a result of acceptable accuracy in computing the inductance of furnace and the difference not more than 3.77% while the difference between theoretical calculations and practical results of tables 2 and 3, certify what was noticed preciously about inaccuracy of equivalent circuit method in estimating the performance of induction heating equipment.

Finally; the successful of design and construction of a small induction furnace with limited abilities pushing us to continue in this way to cover what about the building of induction furnaces.

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Symbols

D_c : Coil diameter (m)

D_w : Charge diameter (m)

K_g : Correction factor

L_c : Coil length (m)

N_c : Number of turns

R_c : Coil resistance (ohm)

R_w : Charge resistance (ohm)

X_c : Coil inductance (ohm)

X_w : Charge inductance (ohm)

X_g : Crucible inductance (ohm)

X_r : relative inductance (ohm)

Z_c : Coil impedance (ohm)

Z_w : Charge impedance (ohm)

δ_c : Skin depth (m)

μ : permeability (H/m)

μ_o : free space permeability (H/m)

μ_r : relative permeability (H/m)

ρ : resistivity (ohm/m)

ω : angular frequency

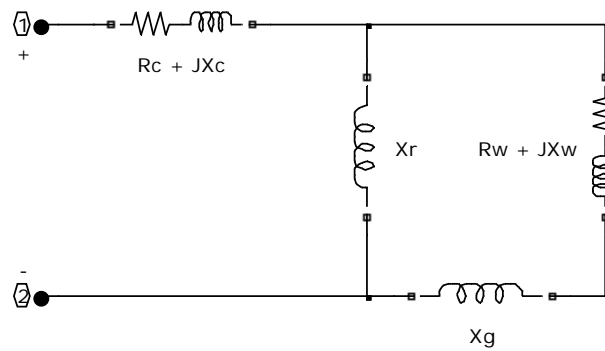


Fig. 1 Equivalent circuit of induction furnace

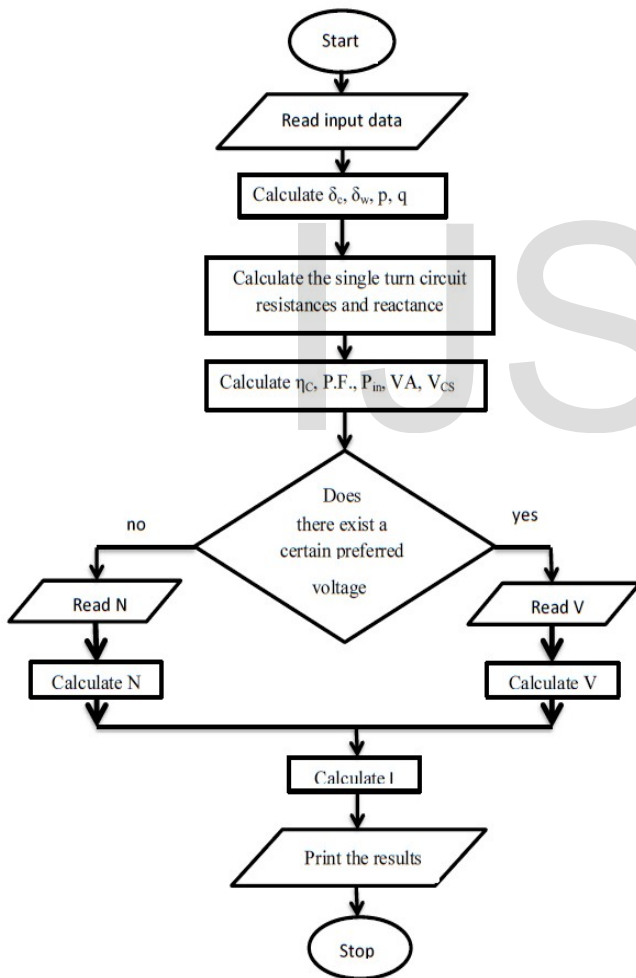


Fig. 2: flow chart Equivalent circuit Method

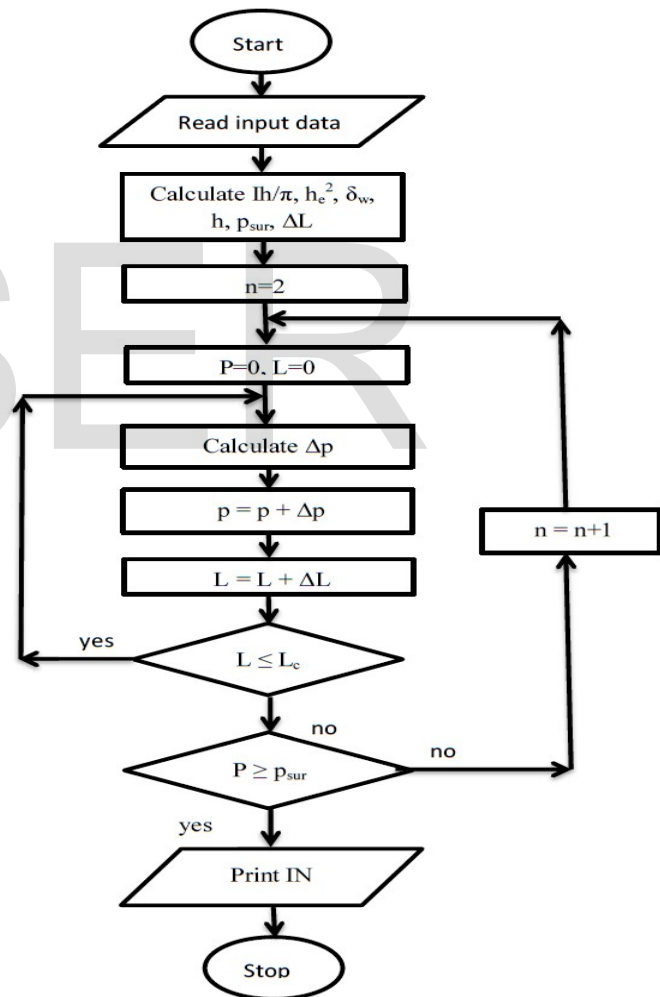


Fig. 3: flow chart superposition Method

Table 1: The dimension of the designed crucible (in mm)

Charge diameter (at the top)	37.31
Charge diameter (at the bottom)	35.14
Charge height	53.25
Coil inner diameter	51.22
Coil height	53.25
Base thickness	23

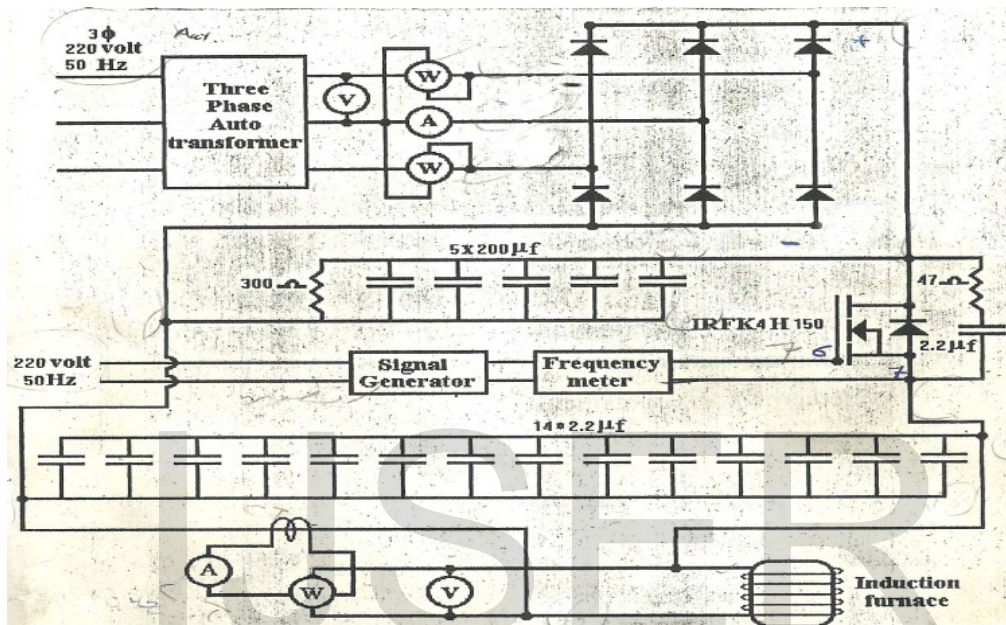


Fig. 4: The circuit diagram of the power supply

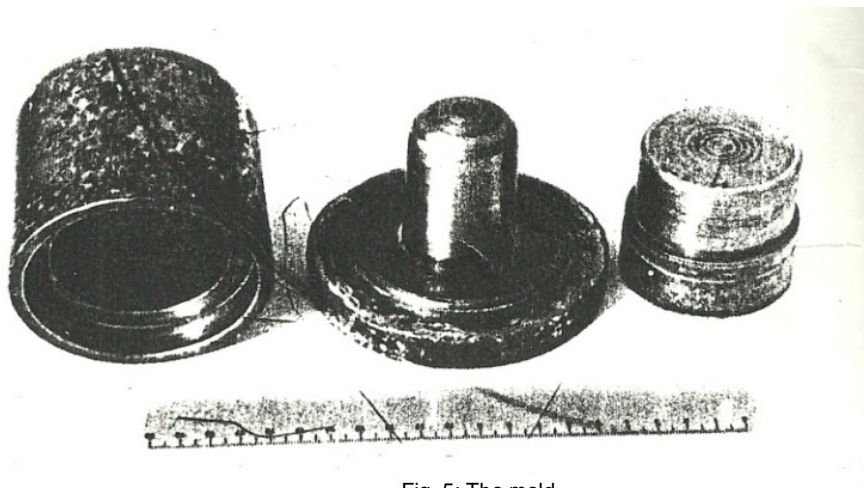


Fig. 5: The mold

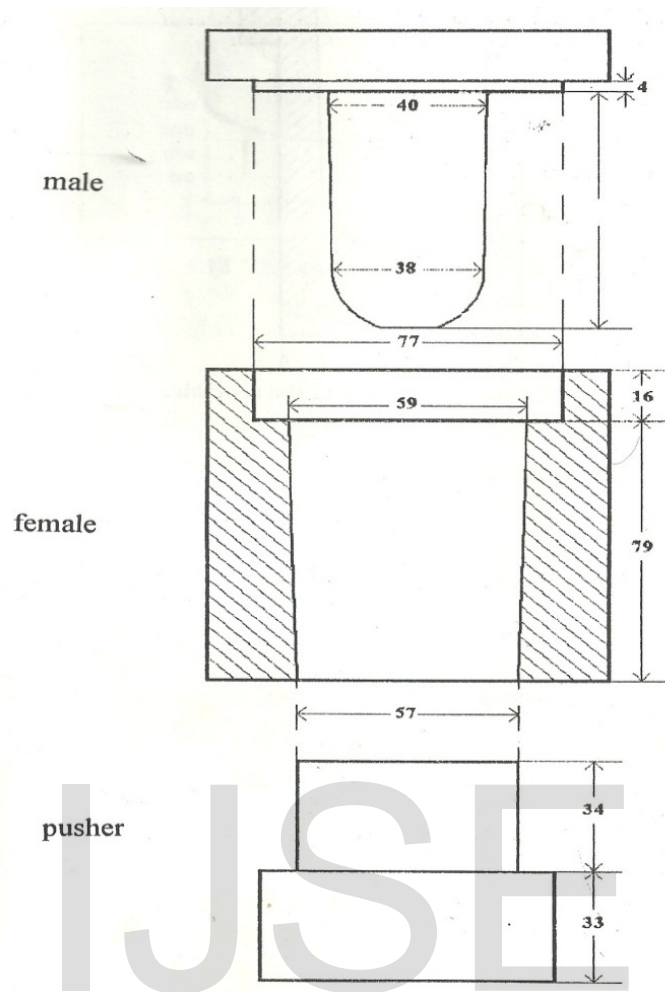


Fig. 6: Cross-section view of the mold

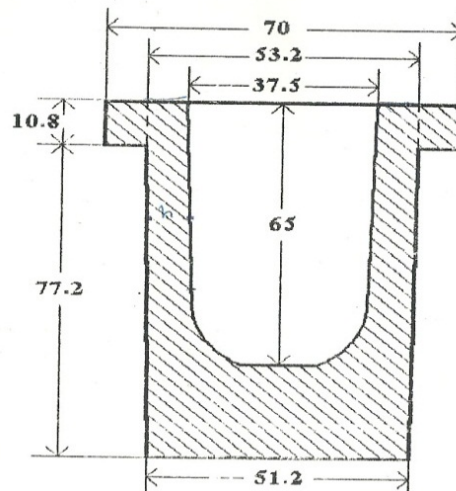


Fig. 7: Cross-section view of crucible

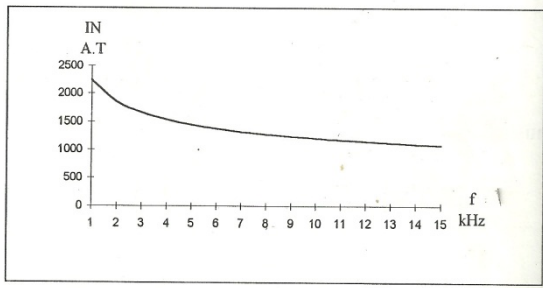


Fig.8 The amper-turns, versus frequency obtained by equivalent circuit method

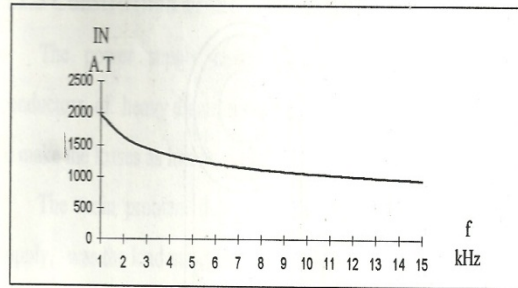


Fig.9 The amper-turns, versus frequency obtained by superposition method

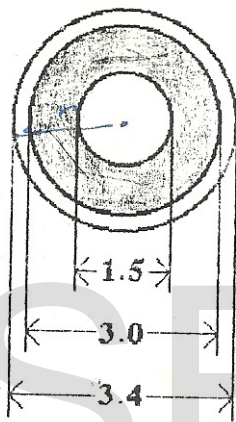


Fig. 10 Cross-section view of the tube

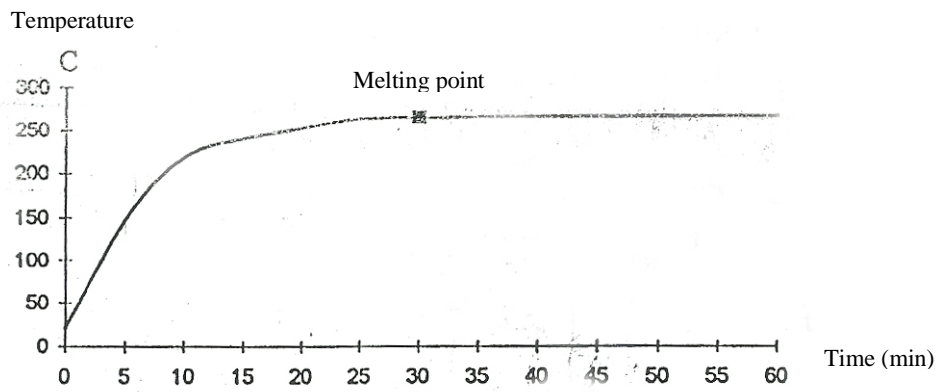


Fig.11: Rise of temperature (12Khz, .125Kw)

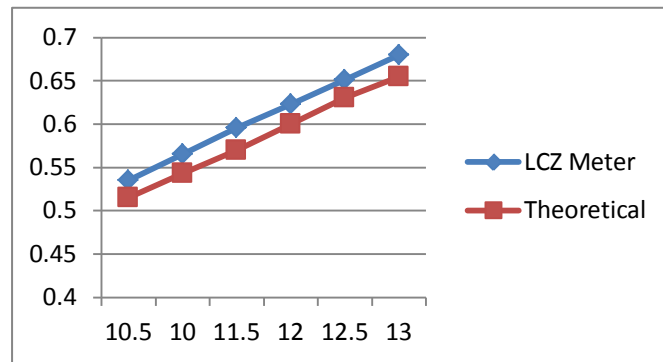


Fig. 12 Furnace impedance

Table 2: The furnace efficiency

Input power (KW)	Frequency (KHz)	Furnace efficiency(%)		Output power (KW)	Melting time (min)
		Practical	theoretical		
0.125	12	16.93	10.14	0.021	30
0.155	12.5	21.01	18.02	0.032	15
0.183	13	33.07	24.37	0.06	10

Table 3: The required amper-turns

Input power (KW)	Frequency (KHz)	Amper-turns (A.T)	
		practical	theoretical
0.125	12	761.22	966.34
0.155	12.5	899.2	1014.7
0.183	13	1001.12	1059.9

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