MODELING AND INVESTIGATION OF FERROFLUID MICRO TRANSFORMER AND INDUSTRIAL TYPE TRANSFORMER

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ABSTRACT: In this study, the results of experimental studies of two practical applications of magnetic fluid are presented. In the first example, the core of the air core small size transformer, whose body is made of non-magnetic material, was filled with magnetic fluid and the output voltage characteristics of different frequencies were investigated. In the second model, the use of magnetic fluids in order to weaken the negative effects of the small cracks and crevices formed on the cores side arms of the industrial transformers to the output characteristics of the transformers were examined. For this purpose, the channels of different types of transformers of the 220V/12V low-voltage transformers with a 5W power rating of industrial PCB type were filled with magnetic liquid and the characteristics of the transformer were examined. In order to increase the magnetization properties of magnetic fluids, pure iron powder (Fe_3O_4) was added to these fluids and experimental investigations were performed. The positive results were evaluated in tables and graphs.

Keywords: ferrofluid, magnetic fluid, magnetic particles, microtransformers, magnetic core, high frequences

1. INTRODUCTION

When the rapidly developing electrical-electronic technologies are examined, it is important to develop high-efficiency, compact systems. In this respect, transformers are among the critical system elements used in the industry. Accordingly, the development of new types of transformers and their optimum design in terms of operation and economic remains one of the most important problems of today. There are many multidisciplinary studies on the development of high-quality, high-efficiency materials and system designs [1]. In particular, it is desirable for the material of the magnetic core to have high quality, high magnetization values. In this context, it is possible to make improvements in the design of materials as well as to reduce the electrical losses caused by metal casing. The magnetic cores in the transformers have higher magnetization is a very important advantage for these systems. In this respect, the use and application of magnetic fluids (ferrofluids) in electromagnetic systems has gained importance in recent years and has become widespread [2]. Magnetic fluids have an important place in many industrial fields such as defense industry, medicine, biology, power systems, heavy industry [3 - 7]. Magnetic fluids have a colloid structure consisting of nano or micron-sized ferromagnetic particles containing a variety of carrier non-magnetic bases (iso-paraffin, oil, etc.). In addition to the magnetization property, such as solid magnetic materials, it is also of great advantage that it exhibits fluid characteristics due to its liquid form. The use of ferromagnetic liquids in the transformers as a core or in a certain part of the body is less than the electrical losses, the lighter the transformer body is one of the important advantages that increase the efficiency and ease of application. Development of transformers which are divided into many sub-branches and specially designed according to their intended use, minimizing the electrical losses and obtaining higher efficiency constitute one of the important engineering problems. In recent years, various prototypes of ferrofluid-core transformers have been created and the design and experimental results of such transformers have been presented in the literature [8 - 12]. In some studies, the structure and experimental results of ferrofluid-core micro transformers are also presented [13, 14]. In these studies, substantially less winding numbers as well as less magnetic fluid were used. In addition, the applied frequency is in the high band and the magnetic fluid used is based on the oil [15]. In contrast, different types of magnetic fluids in the same type of transformers and a greater amount of magnetic fluids may exhibit very different characteristics at relatively low operating frequencies.

In this study, it was made by adding micron sized pure iron powder step by step to the design of small size ferrofluid core prototype transformer and the output characteristics of this transformer at different frequency values were investigated. The magnetic liquid used as the core is an iso-paraffin based liquid prepared in industrial environment (SIGMA HI-CHEMICAL INC). The primary and secondary winding numbers are adjusted for electrical resistance of the prototype transformer. The results are presented and discussed in tables and graphs. In addition, the slots of 0.5 mm and 1,0 mm on both sides of the core arms of the PCB type transformer with the standard industrial type 220/12 V, 5W are opened on core arms are completed with pure iron powder and ferromagnetic liquid for these two values separately, the output voltage characteristics were examined, the results were transferred to the table and compared with the graphs. When the test values of the first transformer were compared with the test results, a value increase was observed on the output voltage values in all cases. The magnetic fluid used is made in industrial (SIGMA HI-CHEMICAL INC) and is iso-paraffin based.

2. MATERIAL AND METHOD

It presented that magnetic fluid (ferromagnetic liquid, ferrocant) and properties of this liquid and magnetization curves will be presented. In addition to the magnetite (Fe_3O_4) particles contained in the liquid to enhance the magnetization properties of magnetic fluids, it is enriched with micron-sized magnetite particles prepared by this liquid industry method. Micro transformers and experimental models prepared with industrial transformers were performed using the magnetic fluid. In the laboratory environment, the input and output characteristics of these transformers were investigated. In laboratory experiments, source, measuring circuits and devices which are present in laboratory conditions are used.

2.1. Magnetic Liquid

Magnetic fluids have been used in many fields of science since the 1960s [1, 5, 6, 15, 16]. Nowadays, many ferromagnetic liquids with different properties are used with different carrier bases according to the usage area and needs. Essentially, the use of magnetic fluids, which are included in the nano and micro technology class, are effectively used in many industrial areas. In experiments manufactured by Sigma Hi-Chemical Inc DS-50 type, the saturation magnetization Ms=50 (Magnetization mT at 1.2MA/m), the magnetic fluid is used. The image of the magnetic fluid used is under the influence of fixed neodymium magnets. One of the most important applications of magnetic fluids is that these fluids can be used instead of metal cores, which are the main elements of the transformers [8 - 10].

Figure 2.1. The response of the DS-50 magnetic fluid to the constant neodymium magnet field.

The magnetization curve graph of the magnetic fluid used (DS-50) compared to other magnetic fluids produced by the manufacturer for general use is given in Figure 2.2.

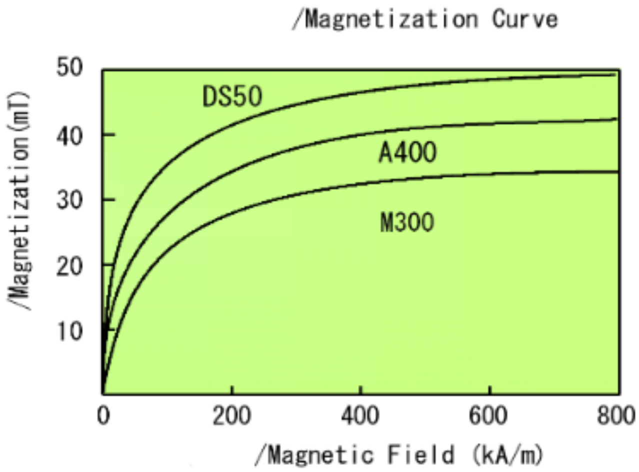


Figure 2.2. Magnetization curves of DS-50 with other magnetic fluids from Sigma CO. [17]

As shown in the graph, the type of magnetic magnetic fluid produced by Sigma is the DS-50 type magnetic fluids with the best magnetization.

2.2. Pure Iron Powder

In order to increase the magnetization property of DS-50 magnetic fluid produced by Sigma in experimental studies, pure iron powder was added or used alone at certain concentrations. For the size of the pure iron powder (magnetite) particles to be comparable to the magnetite particles in the standard DS-50 magnetic fluid , these iron powders were ground in micron-sized particles. The electron microscope image of the ground iron powder is given in Figure 2.3.

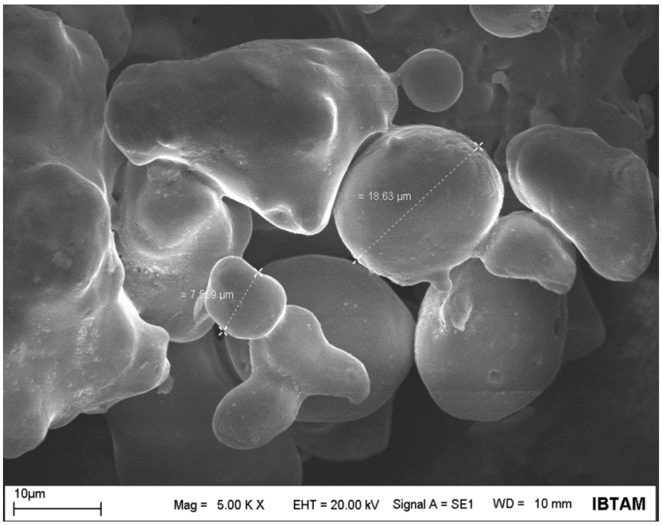


Figure 2.3. Electron microscope image of milled pure iron powder

In this study, pure iron powder was added to the magnetic liquid with different concentrations determined and mixed homogeneously. The resulting magnetic fluid was converted to a liquid having more magnetite (Fe_3O_4). In order to evaluate the magnetization properties of these new magnetic fluids formed, investigations were carried out using pure iron powders alone. The response of the iron powder used to the field of fixed neodymium magnets is shown in Figure 2.4.

Figure 2.4. Interaction of ground pure iron powder with fixed neodymium magnets.

2.3. Design and Investigation of Magnetic Liquid Core Micro Transformer

The designed transformer has a structure consisting of primary and secondary windings round on a 1 ml general purpose plastic syringe. The primary winding was round on the syringe with a 0.3 mm diameter copper wire and a total winding resistance of 77 ohms. It is wrapped with secondary coil with a copper wire of 0.7 mm thickness and a total winding resistance of 0.6 ohms. The designed transformer is shown in Figure 2.5.

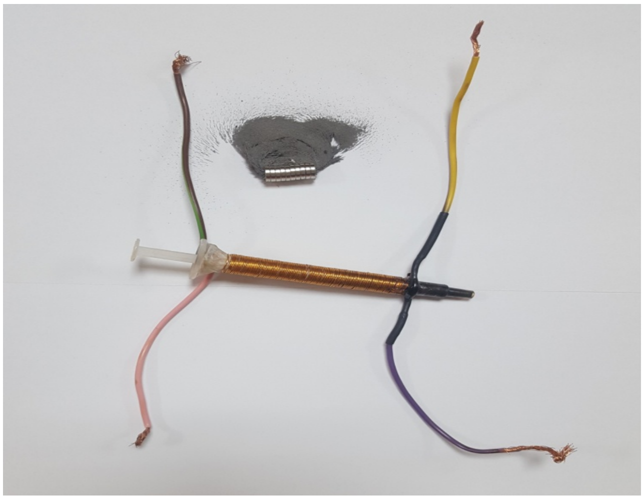


Figure 2.5. Designed micro transformer

2.4. Mantel Type Single Phase Transformer

In this study as a reference transformer VDE 0570 / EN 61558 made according to norms (supplier: Aslan Electronics, Malatya, Turkey) single-phase, 220/12 V, type of standard industrial transformers with PCB 5W electrical values are used. One of the two transformers belonging to the same production batch was used as reference and the other was used with different structural changes. In the other mantel type single phase transformer designed, air gaps of 0.50 mm and 1.0 mm were formed on the side arms of the body. These gaps were filled with DS-50 type ferromagnetic liquid and pure iron powder and open circuit tests of the transformer were performed. The images of the transformers are shown in Figure 2.6.

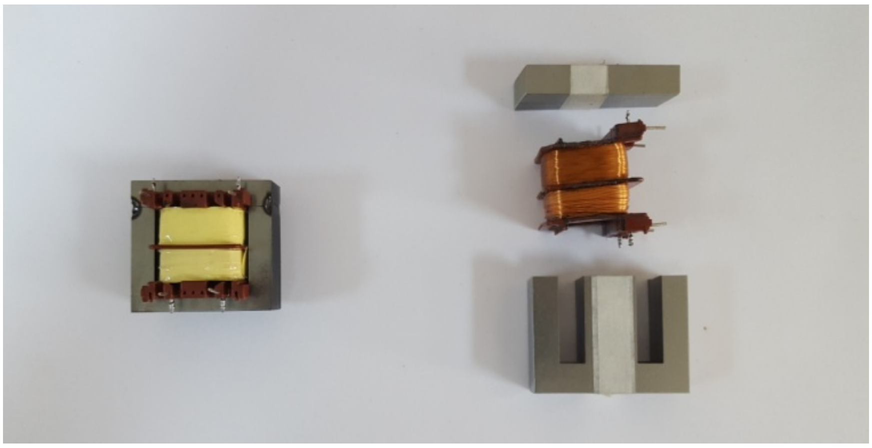


Figure 2.6. Welded, varnished and without welded, unvarnished, disassembled transformers from the same production line.

2.5. Theoretical Concepts

In general, magnetic fluid theory is interdisciplinary and includes the basic concepts of electromagnetic field theory, fluid mechanics, thermodynamics, heat and mass transfer. But in the macro approach, this theory can become more useful. In general, the magnetization of magnetic fluids is determined by the Langevin function.

$$M = M_s \left(coth\xi - \frac{1}{g} \right) \tag{1}$$

Here, the magnetization of M, M_s the magnetization of the magnetic flux,

$\xi = \frac{\mu_0.m.H}{K.T}$ Langevin function, H is the magnetic field strength, the magnetic moment of the particles m, K Boltzmann constant, T absolute temperature, $\mu_{0=}\ 4\pi * 10^{-7}$ H/m. The relative permeability of the magnetic fluid is,

$$\mu_r = \frac{B}{\mu_0 H} \tag{2}$$

To evaluate the Langevin function, the magnetization of the system in large magnetic fields ($\xi \rightarrow \infty$) approaches the saturation magnetization of the magnetic fluid, M = Ms [6].

In weak magnetic fields ($\xi \ll 1$), the magnetization of the magnetic fluid M is linearly proportional to the magnetic field of H.

$$M=\lambda \cdot H \quad (3)$$

Here, λ is the susceptibility of the magnetic fluid. If the concentration of the magnetic phases in the magnetic fluid is ø, then the saturation magnetization of the magnetic liquid

$$M_s= \emptyset \cdot M_1 \quad (4)$$

is determined. Here, M_1 magnetic phase (magnetite) is magnetized. When magnetic fluids are used in magnetic nuclei, the induced voltage, flux and inductance are the same as the cores made of plate,

$$u(t) = L\frac{di(t)}{dt} \quad (5)$$

Here, *L* is the inductance, *i(t)* is the current in the winding. At this time induced magnetic flux,

$$\emptyset(t) = L \cdot i(t) \quad (6)$$

is determined. If the inductance of the winding is *L*,

$$L = \mu_0\mu_r \cdot \frac{N^2 \cdot S}{\ell} \quad (7)$$

S is the section, *N* is the number of windings, ℓ is the length of the winding. The impedance of the winding allows the evaluation of impedance or inductance with frequency.

$$Z = \sqrt{R^2 + (2\pi f)^2} \quad (8)$$

Here *R* is the recessive resistance of the winding, *f* is the frequency.

Assuming that the system is solenoid type when magnetized, the impedance-frequency relation for high frequencies is written in complex form as follows.

$$Z = R + \omega\frac{\mu'' N^2 S}{\ell} + j\omega\frac{\mu' N^2 S}{\ell} \quad (9)$$

ℓ is the length of the solenoid, S is vertical cross-sectional area of the solenoid, μ'' (μ') are the real and virtual parts of the complex permeability of the magnetic winding respectively.

3. APPLICATION AND RESULTS

3.1. Investigation Of Ferrofluid Core Micro Transformer

The signal generator was connected to the micro transformer (Figure 2.5) and the input signal was applied to the primary winding at different frequency values. The effect of the different frequencies applied on the output voltage was observed by open circuit measurements. Measurements were made by adding 1.0 ml magnetic fluid to the core of the transformer which is operated as an amplifier. These measurement results are given in Table 3.1.

Table 3.1. Test results performed by adding 1 ml magnetic fluid to the micro transformer core.

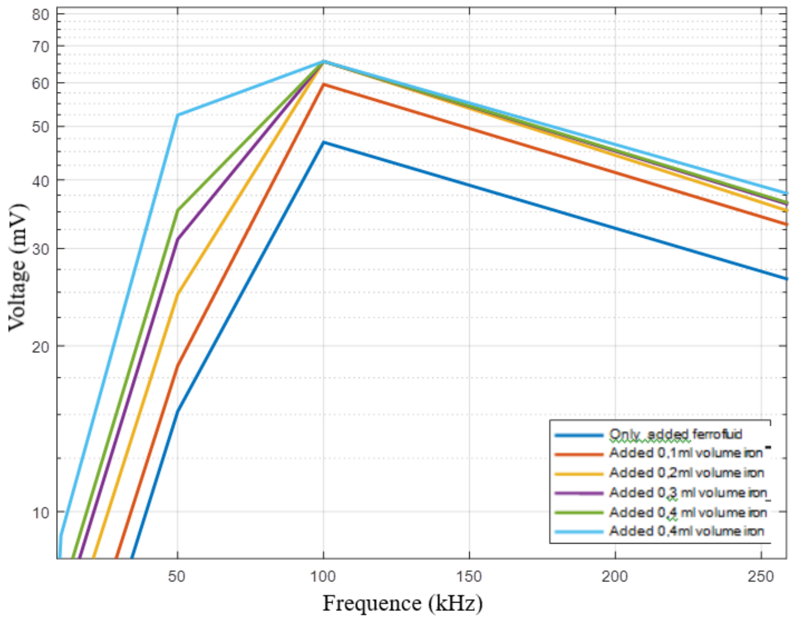
Frequency (kHz)	Primary Input Voltage (V)	Secondary Output Voltage (V)
0.100	0.100	0.055
0.500	0.088	0.168
1	0.100	0.344
10	0.312	3.20
50	1.40	15.20
100	3.92	46.80
1000	5	1.84

However, as seen from the tables, these values are formed from silicon alloy plate or are weaker than the characteristics of ferrite core transformers. Accordingly, it is necessary to improve the magnetization or magnetic properties of the ferrofluid. Generally, these two methods can be achieved:

a) Using new types of magnetic fluids with high saturation magnetization.

b) Improving the magnetic properties of the existing magnetic liquid.

The use of the first method now has a limited level and the saturation magnetization of the best magnetic fluids can only reach 100-140 kA /m. Increasing these values seems to be difficult both physically, chemically and technologically. Moreover, the improvements can cause the price of magnetic liquid to increase. Accordingly, this method will only be eliminated in the future by the creation of high quality high magnetic magnetic fluids with lower cost. The more practical method is the second one. Due to the production of magnetite (Fe3O4) particles in industrial environment or technology production is easy and cost is low. Accordingly, the addition of these powders to a certain concentration of magnetic fluid results in a certain level of saturation magnetization of the liquid. In the experiments, the frequency of the voltage applied to the primary winding of the transformer was varied over a wide range (0,1-...-1kHz). Pure iron powder (Fe_3O_4) was added to the magnetic fluid in the micro transformer core and the measurements were repeated in a homogenous manner.



Graph 3.1. The effect of the amount of pure iron powder added to the micro transformer core on the transformer output characteristic.

As can be seen from Graph 3.1, with the addition of pure iron powder into the magnetic fluid, the output characteristics of the micro transformer started to rise. In other words, by adding magnetic fluids to a non-magnetic core and increasing the magnetic property of the liquid, the magnetic characteristics of the core and, consequently, the operating characteristics of the transformer vary particularly well in the 50-100kHz frequency range.

The major advantage of changing the magnetic property by increasing the magnetite concentration inside the magnetic magnetic fluid is that there is no permanent magnetization in the hysteresis of the magnetic fluids. The disadvantage is the increase in the magnetic particle concentration and the increase of energy losses in the core at high frequencies. However, the effect of this increase on the output characteristics of the transformer in weak power transformers should be examined and evaluated separately. In addition, the addition of different doses of iron powder to the magnetic fluid also changes the classical meaning of these fluids. As can be seen, according to the change of applied frequency values, the most stable frequency range in which the iron powder additive magnetic liquid core micro transformer operates is 50-100 kHz. As the applied frequency approaches 1 MHz, the output voltage induced by the increase of electrical and magnetic losses due to the excessive vibration generated by the high frequency of the nano-sized iron powder particles, which are added during the experiment, as well as their own nano-sized iron particles in the magnetic fluid, is rapidly decreasing. The deteriorated output voltage characteristic can be overcome by choosing another type of magnetic fluid suitable for high frequency operation. Magnetic losses can be minimized in high frequency operations by selecting magnetic fluids containing other magnetic particles (e.g. ferrite) instead of iron powder particles (Fe_3O_4) which cause excessive electrical losses at high frequency.

3.2. Air Gaps on the Core Arms Investigation of a Mantel Type Single Phase Transformer Filled with Magnetic Fluid

In this study, industrial single phase mantel type (Figure 2.6) transformers with single phase, body plate thickness 0.5 mm with 220/12 V voltage and 5W power value were used. Two transformers were supplied from the same production series. The first transformer ready for use is based on reference and no operation has been performed. Part E and I forming the body of the second transformer were not welded and part I was moving freely. Reference measurement value results obtained by connecting adjustable AC source (variac) to transformers are given Table.3.2.

Table 3.2. Actual running voltage values of reference transformer and sisassembled transformer

Input Voltage Applied to Primary Windings (V)	Reference Transformer Output Voltage (V)	Disassembled Transformer Output Voltage (V)
30	1.975	1.975
50	3.285	3.284
100	6.60	6.61
120	7.93	7.92
150	9.899	9.899
170	11.23	11.22
190	12.55	12.54
200	13.20	13.21

As seen from Table 3.2, the real running values of the two transformers are almost the same. It is seen that the body separated transformer and reference transformer have almost the same output characteristics. In the study, air gaps of 0,5 mm are opened in both core arms of the transformer without welding, which can be separated first. The output voltage values obtained by connecting AC variac to the transformer input without any welding process by physically reassembling the body are given in Table.3.3.

Table 3.3. Working voltage values of transformer which has 0,5 mm air gaps on body arms

Primary Winding Input Voltage (V)	Secondary Winding Output Voltage (V)
30	1.677
50	2.839
100	5.744
120	6.97
150	8.70
170	9.87

As can be seen from the table above, the air gap in the transformer body arms has been reduced by an average of 13% on the output voltage.

The air gaps in the two arms of the transformer were filled with pure iron powder (Fe_3O_4) and the body was re-assembled only physically without any welding process. The air gaps of the transformer are filled with iron powder and ready for measurement are given in Figure 3.1.

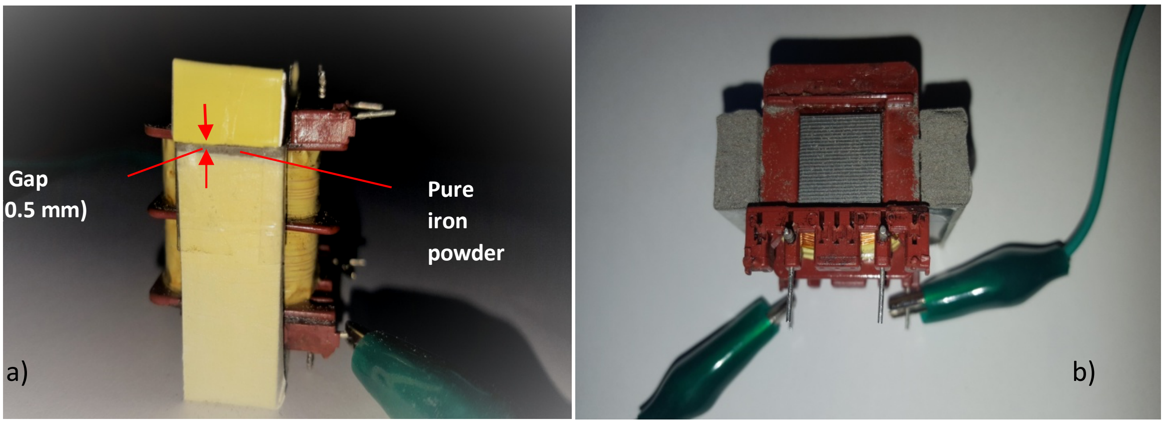


Figure 3.1. Transformer filled with pure iron powder with a 0.5 mm slit on both sides of the body arms. Side view of transformer (a). Top view of crevices (b)

The output voltage values of the 0,5 mm air gap in both arms, which are filled with pure iron powder and connected to the transformer prepared by it, are given in Table 3.4.

Table 3.4. Working voltage values of transformer which is filled with 0.5 mm air gaps completely pure iron powder in the body.

Primary Input Voltage (V)	Secondary Output Voltage (V)
30	1.885
50	3.160
100	6.312
120	7.59
150	9.49
170	10.50
200	13.20

As can be seen from the table, the output voltage values are increased according to Table 3.3 as expected. As a result of the filling of the pure iron powder into the gaps opened, the output voltage values were visibly approached to the reference values (Table 3.2).

After the test air pores were filled with iron powder, the iron powder was emptied and replenished by replacing it with magnetic fluid. In the transformer with air gap in both arms, the gaps are filled with magnetic fluid and the body is only physically reassembled without any welding process. Magnetic fluids filled with the transformer arms are given in Figure 3.2.

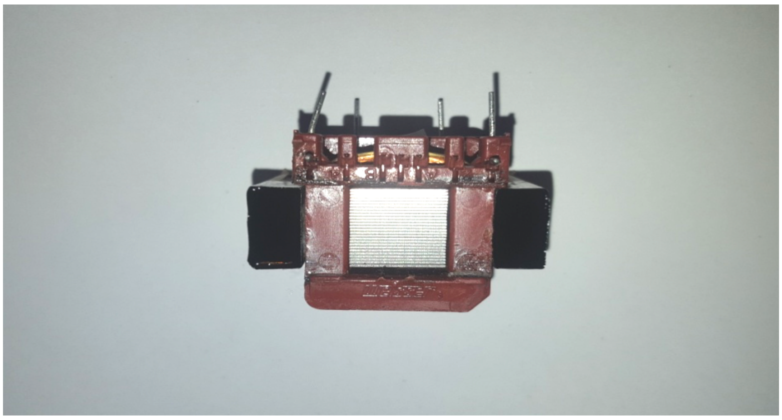


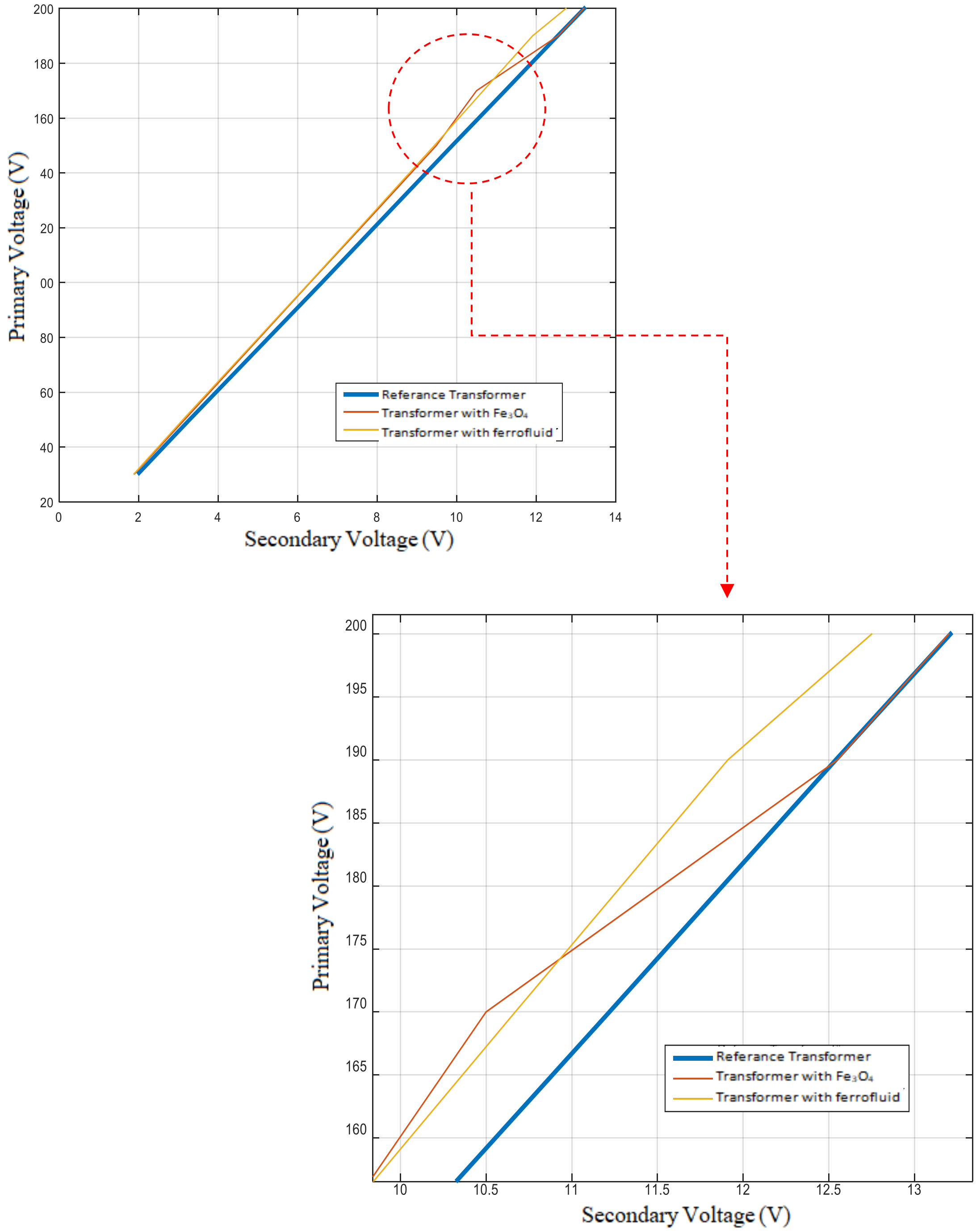
Figure 3.2. Top view of transformer with ferromagnetic fluid added to the core arms

The input / output voltage values obtained by connecting the variac to the transformer prepared by filling the 0.5 mm air gap in the two arms with the magnetic liquid completely and placing the upper part of the transformer are given in Table 3.5.

Table 3.5. 0.5 mm gap in the transformer body are completely filled with ferromagnetic fluid and the obtained measurement results.

Primary Input Voltage (V)	Secondary Output Voltage (V)
30	1.871
50	3.115
100	6.30
120	7.56
150	9.44
170	10.67
200	12.75

As can be seen from the table, the measurements of the experiment with magnetic fluid gave an average output value of 0.72% lower than that of Table 3.4. Increasing the input voltage during the test and the vibration caused due to the fact that the transformer is demounted and not varnished, the magnetic fluid held on the gaps led to minimal moving between the plate. In Graph 3.2, the practical results obtained from the measurements made by adding pure iron powder and then magnetic liquid respectively to the 0.5 mm air gap structure are given comparatively.



Graph 3.2 Comparison of the secondary voltage of the measurements by filling the iron powder and ferromagnetic liquid to the slits by reference output voltage values.

In the above graph, the measurements of the output voltage values of the transformer with pure iron dust and magnetic fluid are compared before any operation of the transformer is performed.

As a result of the open circuit experiments performed, it is observed that the measurements using iron powder are closer to the reference values with a lesser difference.

4. CONCLUSIONS

As a result of the experiments, 1 ml of magnetic fluid was added to the core of the designed micro transformer and then gradually mixed with a total volume of 0.5 ml of iron powder, according to the change of applied frequency values, the most stable frequency range in which the iron powder additive magnetic liquid core micro transformer operates is 50-100 kHz (Graph 3.1). As the applied frequency approaches 1 MHz, the output voltage is reduced as a result of the increase in electrical losses due to the excessive vibration of the nano-sized iron particles in the magnetic fluid and the high frequency of the nano-sized iron powder particles added during the experiment. The deteriorated output voltage characteristic can be overcome by choosing another type of magnetic fluid suitable for high frequency operation. Magnetic losses can be minimized in high frequency operations by selecting magnetic fluids containing other magnetic particles (e.g. ferrite) instead of iron powder particles (Fe_3O_4), which cause excessive electrical losses at high frequency. As seen from Graph 3.2, ferromagnetic liquid and pure iron powdered applications according to the reference transformer have an increasing effect on the output voltage. In addition, the measurements of the hull slits without filling with any material have shown severe heating problems due to increased resistance in the air gap. In the application of pure iron powder, the output characteristics showed almost the same characteristic as the reference transformer values in the application of the voltage values applied to the primary winding above 185 V_{ac}, while the secondary outlet characteristics increased in ferromagnetic fluid application. Large scale transformers used in industry, assembly, transport ın the case of mechanical body damage that may occur at times, the damaged area can be made as rigid as possible and filled with ferromagnetic liquid or iron powder and this filling process can have a positive effect on the output voltage characteristics.

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