PRIMARY RESEARCH

Design and application of unloaded flat transformers with spiral coils

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Abstract

The proposed transformer was designed with flexible spirals, similar to the Archimedes spiral design, to achieve a thin transformer structure. Soft layered magnetic materials were produced by stacking two or more sets of spiral coils on a plane at a short distance from each other and using suitable spacer materials between these coil sets. Accordingly, an innovative, thin, flat, and flexible transformer was created, and its functionality was ensured. The specifications of the spiral coils were as follows: wire diameter = 20 mil, the gap between turns = 20 mil, number of turns = 40, and thickness = 1 OZ. The transformer was designed with a one-layer or two-layer structure for conducting experiments. Coils were stacked directly to change the coil ratio of the transformer. The substrate material was polyimide, which is flexible and can generate a sound when interacting with magnets. The performance of the developed transformer was examined under two coil ratios: 1:1 and 1:2. Different magnetic materials were used between the coil sets to examine the effects of these materials on the transformer performance. Five settings (A–E) were adopted in this study, and the optimal experimental results were obtained in Setting E, and the second-best results were obtained in Setting C. A silicon steel/primary coil/secondary coil/silicon steel structure was used in Setting E. The output voltage and current were 0.22 V and 12.6 mA, respectively, at a coil ratio of 1:1, as well as 0.49 V and 8.7 mA, respectively, at a coil ratio of 1:2. In Setting C, a magnet/primary coil/secondary coil/magnet structure was used, and the output voltage and current were 0.20 V and 9.27 mA, respectively, at a coil ratio of 1:1 as well as 0.46 V and 7.45 mA, respectively, at a coil ratio of 1:2. The experimental results revealed that the performance of a flat transformer is mainly affected by the spacing between the primary and secondary coils and not by the magnetic material between two coil sets. The secondary coils generate the maximum voltage and current when the primary and secondary coils tightly fit together without any spacer material.

I. INTRODUCTION

Transformers are critical components of AC circuits. In existing transformers, EI silicon steel wrapped with several layers of coils is used to achieve the required coil ratio. Consequently, transformers are bulky and occupy a large vertical space. The transformer designed in this study contains flexible spirals. Its coil design is similar to that of the Archimedes spiral to achieve a thin transformer structure. Soft layered magnetic materials were produced by stacking two or more sets of spiral coils on a plane at a short distance from each other and placing suitable spacer materials between the coil sets. This enabled the creation of an innovative, thin, flat, and flexible transformer while maintaining its functionality. The transformer developed in this study does not contain an iron core. Instead, it only contains two sets of coils that fit tightly together to transmit the induced voltage effectively. To test the performance of the developed transformer, the changes in its induced voltages were examined when using different spacer materials between coil sets. The results indicated that even when non-magnetic materials were used as the spacer material, the developed transformer functioned effectively and exhibited a good conversion efficiency.

In this paper, spiral coils use in the research as a source dif-

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ferenced; it bases on a speaker study by J. M. Lin, C. H. Lin, that the flat coils element was designed for the loudspeaker, but coils prototype thin, flat, and limited working space, transfer coils unit to apply flat transformers result in a unit of flat coils not only flat but prototype have very good electromagnetic properties, transformation to apply in transformers location will have the advantage of thin, light, and compact structure, a unit just suitable for advance flat transformers research.

II. LITERATURE REVIEW

Early transformers contained large iron cores. With reductions in the size and electricity use of circuit components, transformers become lighter, thinner, and flexible; this topic is still under research such as:

[1] designed a dry-type transformer using different winding types for applications; an experiment device is large.

[2] apply non-linear loads such as rectifiers, electronic phase control, and PWM drives, giving rise to a vastly increased level of harmonics in the power network, simulation magnetic flux density (T) distribution result.

[3] To satisfy the test requirements of the superconducting cables, a large CICC test facility has been developed at the High Magnetic Field, and the samples are. For our test facility, the samples are spiral structures and are tested in the solenoidal magnet system, a transformer of experiment with large size, but it was designed for very high current (kA), simulation by ANSYS, and design by using the vertical coil.

[4] research that steel-cored cables with an odd number of aluminum layers are affected by an electromagnetic phenomenon called the transformer effect due to the core's magnetization. They study that power utilities are facing a need to increase the power transmission capacity in existing circuits, be it for environmental restrictions or the high costs related to the construction of new transmission lines. Prototype print and photos show that a transformer has some size, but a traditional transformer always needs a certain size.

[5] studied a Portable Fiber-Optic Current Transformer (P-FOCT) with a flexible sensing coil proposed in this paper. The model has been established to describe the Faraday phase shift errors; this is a mathematical analysis and simulation.

[6] have done amazing research, they used a coil like this paper used, but the MEMS process designed the size of coils and circuit. This work reviews integrated transformers for galvanic isolation, particularly focusing on their modeling in power transfer systems, circuits, and experimental work.

[7] have used the new trend in power converters to design planar magnetic components at a low profile. However, the AC losses induced in the planar inductor and transformer windings at high frequencies become significant due to skin and proximity effects. This research has a planar transformer design and prototype by using a rectangle coil,

[8] designed a particular transformer copper-circuit structure on a flexible baseboard by a laser process. This paper demonstrates the performance analysis of bendable transformers with magnetic core. The transformers are fabricated by laser ablation. The fabrication method is green and on demand. Transformers are important components for switched power supplies; this is interesting research.

[9] present a digital polar Doherty PA with transformer-based input and output passive networks. The point of interest was the design wireless antenna that has an octagon circuit line and made flat spiral coils design.

[10] designed a square spiral inductor structure, the design of passive on-chip capacitor and inductor are key components for RFIC/MMIC design techniques such as filters and oscillators; they design a square spiral coil like as FEPLs with square-type copper coils.

[11] present simulation research on one-cycle square shape Helmholtz coils.

[12] have presented valuable research that fully derives a new model based on the partial inductance method from calculating the mutual inductance between two planar spiral coils with an arbitrary number of sides. Regular concentric polygons approximate the planar spiral coils, and each polygon is decomposed to its sides. This reference simulation and mathematic analysis of any spiral coils: Hexagon type, Octagon type, circular loops type, a prototype of the coil has made on board.

[13] to improve the magnetic field sensitivity of Giant Magnetoimpedance (GMI) sensor at the low frequency, authors reported a laminated magnetic multilayer with coupled exciting and sensing planar coils, a paper study the (GMI) effects by simulation. The coil type was not shown in the photo.

[14] propose several planar micro-electromagnetic actuators that can be applied in micro-pumps and micro-valves. The various types each consist of a Thin Film Permanent Magnet (TFPM), a micro-coil, and, in some cases, a ferromagnetic layer. A paper has some time but analysis many differences Micro electromagnetic actuators on silicon board, including square-type coils.

[15] present a new planar electromagnetic energy harvesting transducer. The transducer can be realized with low-cost printed circuit board technology, leveraging recent ad-

vancements in manufacturing multi-pole magnetic sheets. Reference has had some time too, but energy harvest is still a new topic, and analysis of multi-pole plate magnets and design of square-type coils on board have made prototypes. [16] study proposes a comprehensive analytical model of the magnetism, electrostatics, and loss mechanisms of a simple and economical structure with a printed circuit board-embedded magnetic component (coil, high leakage transformer, or resonator) for electric power conversion in the range 1 W-100 W. This present paper analysis PCB-embedded power conversion type design, use double sandwich spiral coils, two of spiral coils have a trench between each other.

[17] present a detailed theoretical analysis, derivation, and calculation of the electric vehicle wireless power transmission system's working characteristics. The experiment device structure is like us, spiral coil too, turn of the coil not so many times, but prototype size is very large.

[18] discuss the losses analysis of low-power high-frequency Wireless Power Transfer Systems (WPTSs). The point is that this research was designed to experiment with square-type coils for WPTSs-inside and outside, the smaller coil inside, larger coil, not the same size of coil one-by-one.

[19] present a resonant transmitter-receiver system described for wireless energy transmission at a useful distance for grid-coordinate power and information. A reference has some long times, but the analysis coils are spiral type and turn very like ours, the mathematic analysis result very valuably.

[20] review the Wireless Power Transfer (WPT) concept offers users freedom from annoying wires and allows seamless powering and charging of portable devices in an unburdened mode. This view summarizes many WPT circuits and applications, all of the research has a chance to apply to our flexible spiral coils, which are full of opportunities and challenges.

The key contribution of this dissertation is to present a modified planar-type Archimedes' spiral coil design method for use in Flexible Electrodynamic Planar Loudspeaker (FEPL).

The research principle was to use flexible spiral coils, fix a block on the magnet, and align the center when the noise goes through a coil, spiral coils resonance and generate induced EMF. Harvesting energy and could be charge energy saving devices, this method as wireless charge similarly [21, 22, 23].

"An electro-acoustic transducer includes an insulated flexible substrate, a base, and a magnetic field generator. The base includes a cavity, and a magnetic portion disposed below the cavity. The insulated flexible substrate is configured to cover the cavity. The magnetic field generator can be disposed of on the insulated flexible substrate and corresponds to the cavity. The magnetic field generator can produce a magnetic field and a reverse magnetic field to cause the magnetic field generator and the magnetic portion of the base to attract and repel each other, thereby vibrating the insulated flexible substrate."

Since it is much easier to draw the square-type coils, the parameters of square-type copper coils are defined, and a preliminary design for a FEPL [24] is followed. A more detailed design and trade-off study will be given in the next. Fig. 1 shows the structure of the FEPL; it is very simple to place and fix a flexible thin film diaphragm (polyimide) with a copper coil over a magnet (adhered at the bottom of a cavity). The advantage of this new design is that the resistance of the copper coil (4.5-21.8 Ω) is much lower than the previous one with aluminum (20-150 Ω) [25]. Thus it is easier to match with the output resistance of the audio amplifier (4-8 Ω).
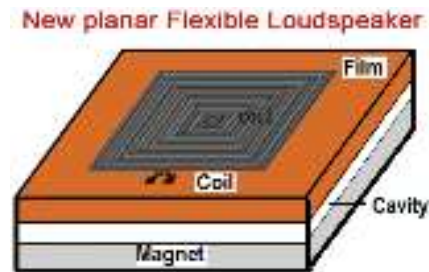

Fig. 1. This research unit of the typical structure of the FEPL with square-type coils [21]

Fig. 2 shows eight square-type diaphragms with different dimensions; they are made on a flexible PCB with Polyimide (PI) as the substrate. Fig. 3 shows the setup of the FEPL tester using NI USB 4431, respectively.

The coils are copper lines, and the DC resistance of each coil is shown in Table 3 for reference. The magnetic intensity for each type of magnet is 2300 gausses (from Taiwan Top Magnets Company), and with the following dimensions:

1) Disc-type for No. 1~4: Diameter φ = 10 mm, thickness H = 2 mm.

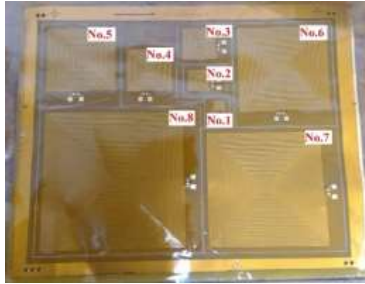2) Square-type for No. 5 ~ 8: Dimension: L = 40 mm, W = 40 mm, H = 4 mm.

Fig. 2. Layout of several dimensions of FEPLs with square-type copper coils using flexible Print Circuit Board (PCB) with Polyimide (PI) as the substrate

Fig. 3. Setup of FEPL tester using NI USB 4431for SPL measurement

TABLE 1
DC RESISTANCE OF EACH
SQUARE-TYPE COPPER COIL

No.	Turns	D.C. Resistance (Ω)
1	5	4.5
2	10	5.4
3	15	6.0
4	20	6.8
5	30	9.1
6	40	12.6
7	50	16.9
8	60	21.8

TABLE 2
SPECIFICATIONS OF MODIFIED COILS

Curve separation (D)	20 mils
Line width	20 mils
Board thickness	0.7 mils
Circuit layers	2 (double sides)
PCB layers	3
PCB material	Polyimide
Center pin-hole radius	12 mils

Design spiral coils can solve problems and increase extended application study locations to increase performance and decrease problems on square-type coils. Spiral coils, as shown in Fig. 4, characteristic of spiral coils as in Table **??**. Finally, the FEPL research has a follow production tree of spiral coil design, including this paper, they were supporting used the FEPL research more applications as Fig. 5.

Spiral coils were as good as applications not only for flat speakers but using wireless charge, energy harvest, and flat transformer research, which is the main target of the paper. A transformer of this paper was using Version B coils; first, the extended study will use another version.

The transformer design developed in this study is revolutionary and surpasses those developed in the studies above. The designed transformer is thin, contains flexible spirals, and can sustain external pressure.
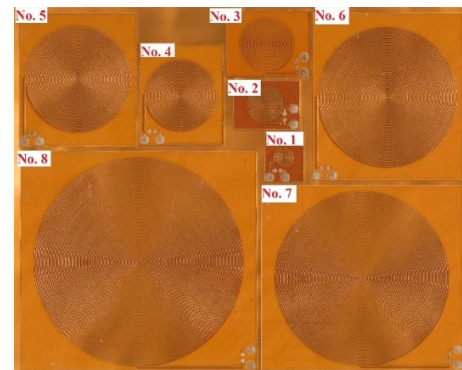

Fig. 4. The layout of several different dimensions of FEPLs with spiral-type copper coils

TABLE 3
DC RESISTANCE OF EACH
SQUARE-TYPE COPPER COIL

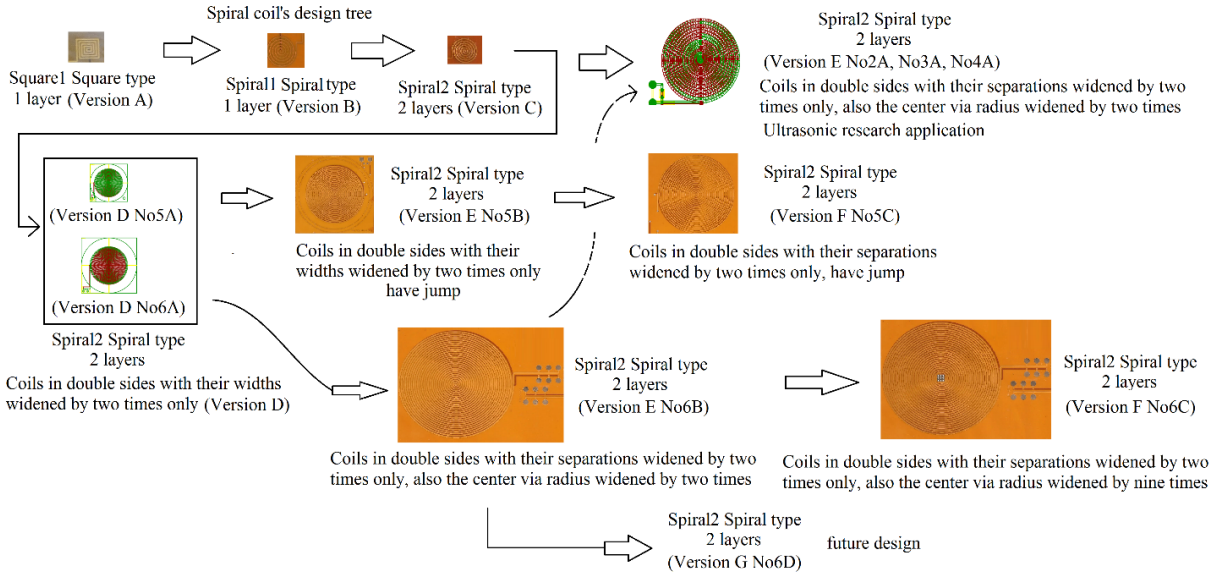| No.	Turns	D.C. Resistance (Ω)
1	5	1.277
2	10	2.12
3	15	3.371
4	20	5.342
5	30	10.467
6	40	17.276
7	50	26.926
8	60	38.783

Fig. 5. Spiral coil design tree

III.   RESEARCH METHOD

The circuit diagram of the developed transformer is displayed in Fig. 6, in which VS, RS, and RL denote the power source, coil impedance, and loading impedance, respectively. Experiments were conducted to examine the transformer voltage at the two ends of the loading impedance at the RL loading end after the flat transformer passed through the 1: N flat transformer spiral. The specifications of the spiral coil were as follows: wire diameter = 20 mil (0.508 mm), gap between turns = 20 mil (0.508 mm), number of turns = 40, and thickness = 1 OZ. The transformer was designed with a one-layer or two-layer structure for conducting experiments. Coils were stacked directly to change the coil ratio of the transformer. The substrate material was polyimide, which is flexible and can generate a sound when interacting with magnets. Fig. 7 depicts one of the coils used in the developed transformer.

Two coil ratios were used for the developed transformer in this study: 1:1 and 1:2. Different magnetic materials were used between two sets of coils to examine the effects of these materials on the transformer performance (Fig. 8–12).
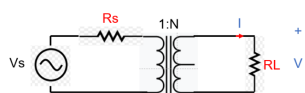
Fig. 6. Circuit diagram of the developed transformer

(1) The structures of the transformer in the performed experiments were as follows:

A1: magnet/coil N/ferrimagnet/coil N/magnet
A2: magnet/coil N/ferrimagnet/coil 2N/magnet
B1: silicon steel/coil N/ferrimagnet/coil N/silicon steel
B2: silicon steel/coil N/ferrimagnet/coil 2N/ silicon steel
C1: magnet/coil N/coil N/magnet
C2: magnet/coil N/coil 2N/magnet
D1: coil N/silicon steel/coil N
D2: coil N/silicon steel/coil 2N
E1: silicon steel/coil N/coil N/silicon steel
E2: silicon steel/coil N/coil 2N/silicon steel
2) The performance of the transformer when using coil N and coil 2N was compared.
3) The audio frequency in the experiments was 20–400k Hz.
(4) The permanent magnet adopted in this study was a Nd-FeB magnet with a magnetic induction of 2500 Gauss.
The developed transformer and its parts are shown in Fig. 13–16. The primary-end signal was generated using a GAG 810 signal generator, and an NI 4072 signal capture card was used at the receiving end to receive signals. An electricity meter was used for verification.
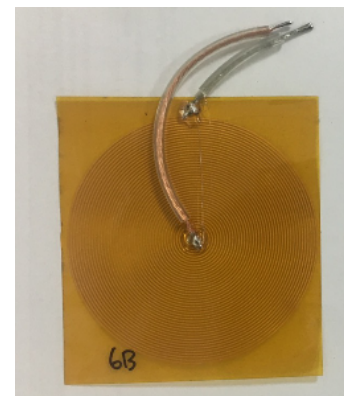

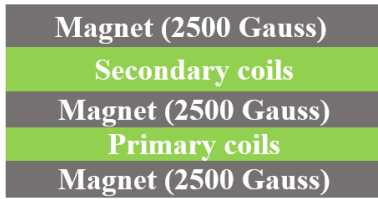Fig. 7. One of the spiral coils used in the developed transformer

Fig. 8. Addition of magnets between the coils in the unloaded flat transformer. (A1 and A2)
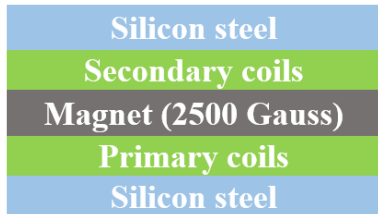

Fig. 9. Addition of magnets between the coils in the unloaded flat transformer. Silicon steel was added outside (B1 and B2)
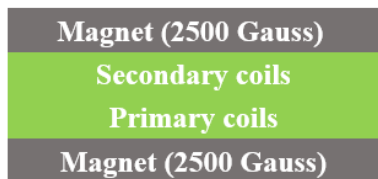

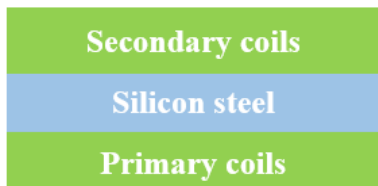Fig. 10. Use of two magnets to clamp the coils of the unloaded flat transformer. (C1 and C2)

Fig. 11. Silicon steel placed between two coils (D1 and D2) in the transformer
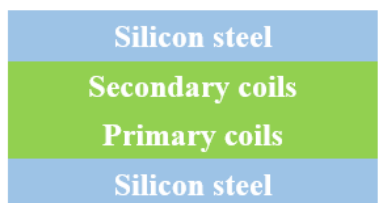

Fig. 12. Silicon steel clamping the transformer's two coils (E1 and E2)
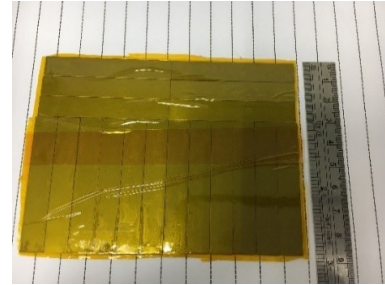

Fig. 13. Silicon steel structure used in this study (used in the experimental structures B, D, and E)
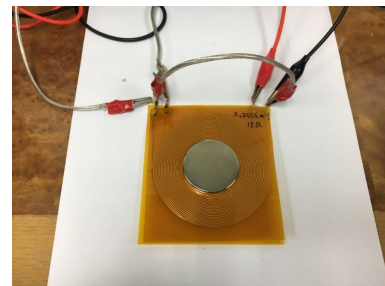

Fig. 14. Permanent magnet and coil modules used in this study (used in the experimental structures A, B, and C)
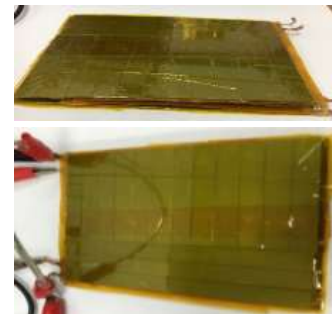

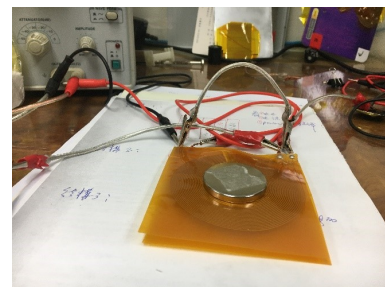Fig. 15. Experimental modules used in experimental structures D and E of the transformer

Fig. 16. Flat transformer during an experiment

IV.   EXPERIMENTAL RESULTS

The experimental method Architecture Diagram as shown in Fig. 17, set Primary coils on GAG-810 signal generator for difference experiment frequency output and then used TDS 1012B Oscilloscope verify signal doing the initial check set voltage of signal generator on Primary coils was 11Vac. Later take Secondary Coils Voltage/Current by DM2630 electricity meter and NI PXI-4072 electricity meter card. Precision measurement (Set in NI PXI 1033 5-Slot, Integrated Remote Controller PXI Chassis) Got Accurate Data, measured data accuracy.
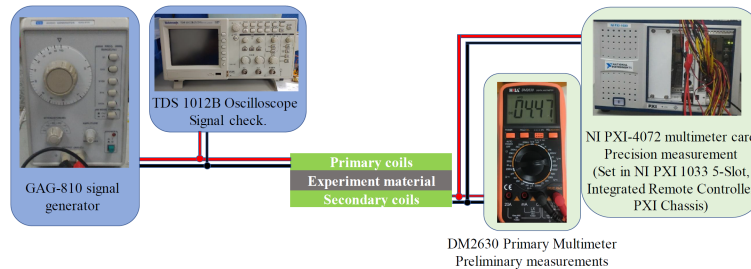

Fig. 17. Experimental architecture diagram

Experimental flow chart as shown in Fig. 18. the First step was to set frequency output, the next was verified by TDS 1012B Oscilloscope, and then sensing output inductive voltage/current. If the output result were not reasonable or unstable output caused by environments interfering, going backward, adjusting cable, and making transformer Flatness, it could keep interference.
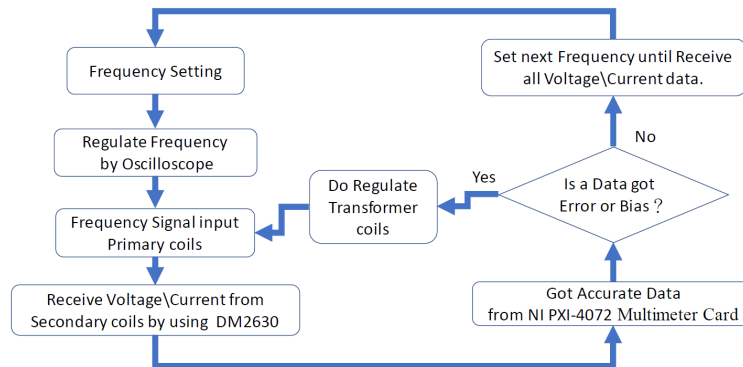

Fig. 18. Experimental flow chart

The experimental results of this study are illustrated in Fig. 19-28. Fig. 19 and 20 display the experimental voltage–frequency and current–frequency plots obtained for structures A1 and A2.
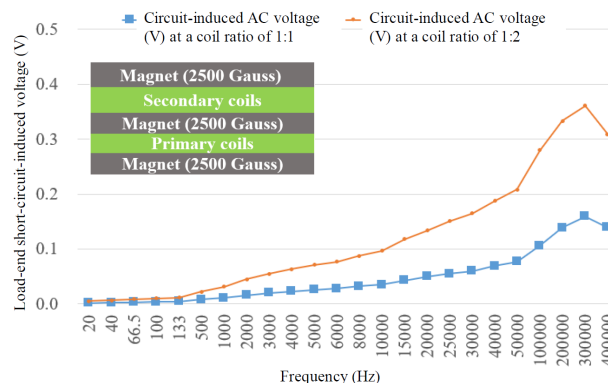

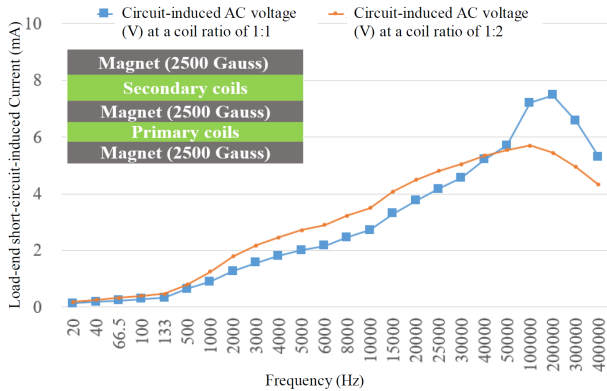Fig. 19. Voltage–frequency plot obtained for structures A1 and A2

Fig. 20. Current–frequency plot obtained for structures A1 and A2

In Fig. 19-20, voltage and current are also increased with positive correlation, coil ratio 1:1 voltage from 0 to 0.16(V), current from 0 to 7.7 (mA). Coil ratio 1:2 voltages from 0 to 0.37(V), current from 0 to 5.8 (mA), a transformer is maiming on voltage increase work, 0.16V and 0.37V have double between ratio 1:1 and 1:2, it shows up transformer workable, experiment successfully.

Following input frequency rise, especially curve has a sharp turning point and upwards about 50kHz. But current between coil ratio 1:2 shows a cross over at the same frequency, which means current does not shape rise at 50kHz in Fig. 20, later smoother decrease performance.

And then, the current both decrease when the frequency rises over 200kHz, the coil ratio 1:1 curve decrease very fast in Fig. 20, and the voltage decrease at 300kHz, which may cause by the frequency limit; the flat coil couldn't work over 30Hz, but it, not a problem suitable of power transformer, usually power transfer not work at the high frequency.

Fig. 21 and 22 display the experimental voltage–frequency and current–frequency plots, respectively, obtained for structures B1 and B2.
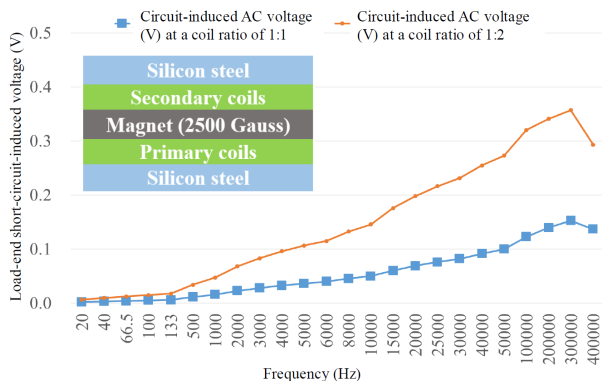

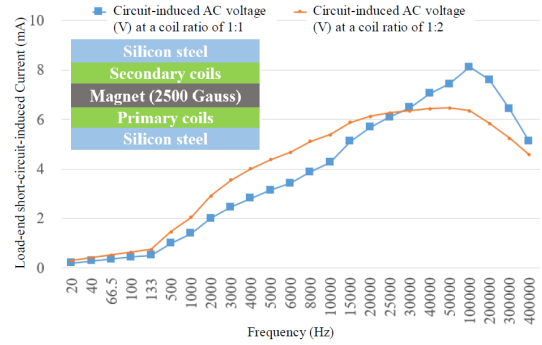Fig. 21. Voltage–frequency plot obtained for structures B1 and B2

Fig. 22. Current–frequency plot obtained for structures B1 and B2.

Fig. 21 shows the voltage of coil ratio 1:1 as 0 to 0.15 and coil ratio 1:2 as 0 to 0.37; both curves have increased with frequency rise, and voltage ratio has also stand 1:2, the voltage of coil ratio 1:2 has a little higher than double have some leeway be using transformer deviation buffering. In Fig. 22, two curves cross over at 27.500kHz, a frequency lower than Fig. 20, showing the impact of replacing the top and button material of a flat transformer.

Fig. 23 and 24 display the experimental voltage–frequency and current–frequency plots obtained for structures C1 and C2.
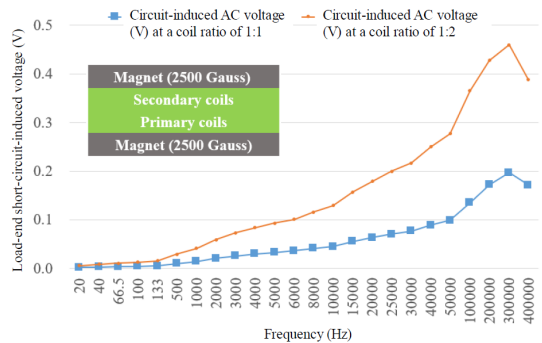

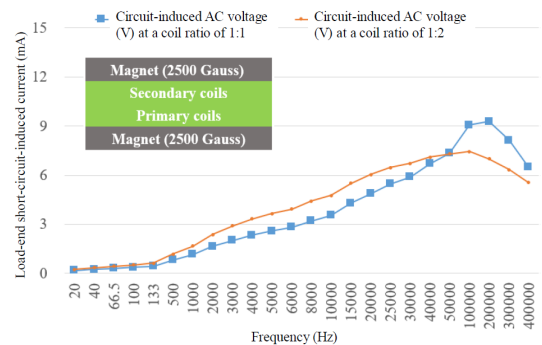Fig. 23. Voltage–frequency plot obtained for structures C1 and C2

Fig. 24. Current–frequency plot obtained for structures C1 and C2

In Fig. 23, the Top voltage becomes higher than in Fig. 19 and 21 at 300kHz, and the curve is sharper than in the

two figures. An interesting flat coil transformer show is very suitable for high-frequency case power transfer; two curves both increase from 20Hz to 300kHz, until the limit at 300kHz, stops the increased voltage; this type of flat transformer is suitable for using high frequency especially. Another has shown that material is not needed between primary and secondary coils; it is very different from traditional transformer design.

In Fig. 24, the frequency of the current curve over the back to 50kHz was similar to Fig. 20; it meant changing the top and button material of flat transformer not very useful until this case, the curve has similar figure 20 too, but Compare Fig. 22, top and button use silicon steel got a higher curve in lower frequency location, it shows silicon steel can be extended low frequency working area, top and button use silicon steel has a good choice.

Fig. 25 and 26 display the experimental voltage–frequency and current–frequency plots obtained for structures D1 and D2.
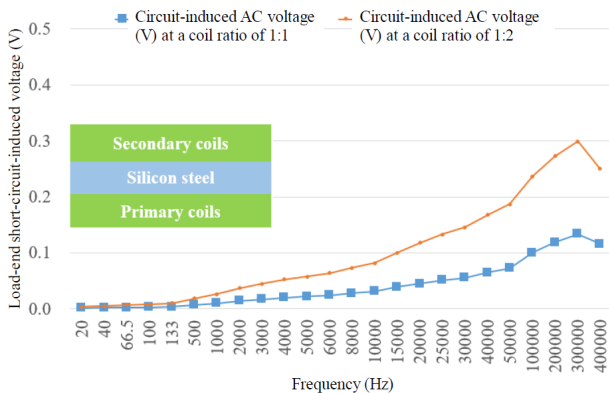

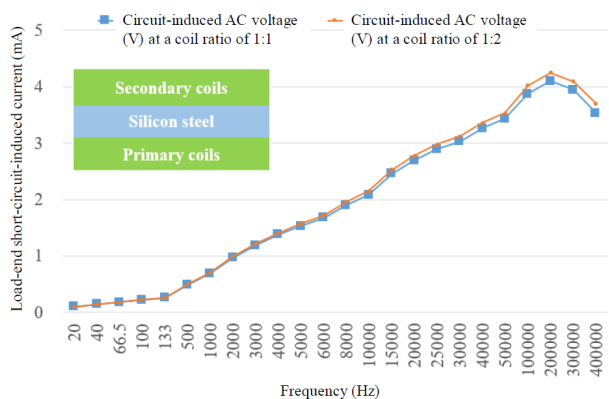Fig. 25. Voltage–frequency plot obtained for structures D1 and D2

Fig. 26. Current–frequency plot obtained for structures D1 and D2

Fig. 25 all frequencies of this data curve show silicon steel sandwich between primary and secondary coils was a bad idea that all of the voltage was lowest than Fig. 19, 12, and

23, silicon steel has to be on top and under the button, not sandwich it.

In the case of Fig. 26, the curve did not cross over was an obvious difference between Fig. 20, 22, and 24, two of the current curves as the same as each other. In the working case, the user only cares about the voltage changer effect with coil ration 1:2 and more, ration 1:1 just like a wireless charger, not a transformer; it is not the point of discussion. Fig. 27 and 28 display the experimental voltage–frequency and current–frequency plots, respectively, obtained for structures E1 and E2 of the transformer. Table 4 presents the maximum voltage currently exhibited by the transformer in the five experimental settings (A–E).
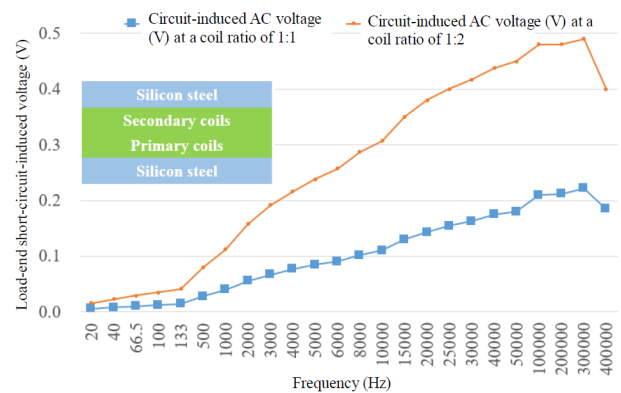
Fig. 27. Voltage–frequency plot obtained for structures E1 and E2
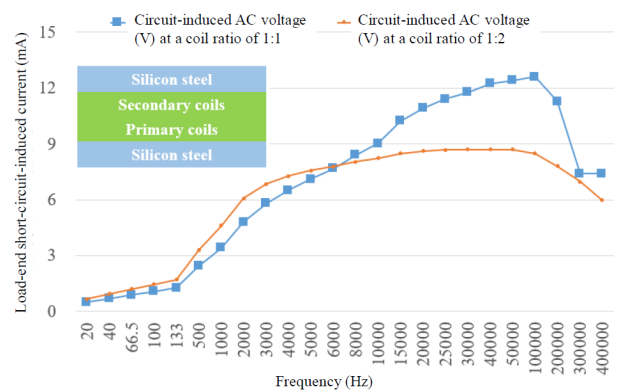
Fig. 28. Current–frequency plot obtained for structures E1 and E2

Fig. 27 shows a voltage not higher than 0.5 volts, but a curve has the highest voltage compared to Fig. 19, 21, 23, and 25; not only this case has the best voltage, but it also has the largest space under the curve, the low-frequency response was best too in all of the cases. Another good thing is it had more wide high voltage from 100kHz to 300kHz; this case will be suitable for low frequency to high; this design was the best choice, but not sandwich anything between coils. Fig. 28 shows this is the best choice, too; the current area

under the curve has the largest space and a more stable trend between frequency 133 Hz and 100kHz; this case has the best stable performance current area. Table 4 shows all cases' voltage and current ratios, meaning all cases have an amplified voltage effect, but the table couldn't show the working area under curves.

TABLE 4

VOLTAGE AND CURRENT DATA OBTAINED FOR THE DEVELOPED TRANSFORMER IN FIVE EXPERIMENTAL SETTINGS (A-E)

Structure of Transformers	Max Output (V)		Max Output (mA)	
Coils Proportion (Primary/Secondary)	1:1	1:2	1:1	1:2
A. Meg/coils/Meg/coils/Meg	0.16	0.36	7.47	5.70
B. Silicon steel/coils/Meg/coils/Silicon steel	0.15	0.36	8.11	6.46
C. Meg/coils/coils/Meg (Second good)	0.20	0.46	9.27	7.45
D. coils/Silicon steel/coils	0.13	0.23	4.10	4.25
E. Silicon steel /coils/coils/Silicon steel (Best)	0.22	0.49	12.60	8.70

V. CONCLUSION

A. Experiment Result

Table 3 presents the maximum voltage and current of the unloaded flat transformer in five experimental settings.

1. When the coils in the center of the transformer were fit tightly together, and the outer part of the transformer contained a magnet or silicon steel structure (i.e., Settings C and E, respectively), the output voltage and current were optimal. Thus, the most critical task was to make two coils fit as tightly together as possible.

2. When the center of the transformer contained a silicon steel structure and the outer part contained coils (i.e., Setting D), the worst transformer performance was achieved. Thus, the transformer performance worsened when the coils were not tightly fit together.

3. When the inner and outer parts of the transformer contained a magnet (i.e., Settings A and B), the second-best transformer performance was achieved. Thus, the higher the magnetism, the higher the eddy loss.

The optimal experimental results were obtained in Setting E, followed by Setting C. In Setting E, the output voltage and current were 0.22 V and 12.6 mA, respectively, at a coil ratio of 1:1, as well as 0.49 V and 8.7 mA, respectively, at a coil ratio of 1:2. In Setting C, the output voltage and current were 0.20 V and 9.27 mA, respectively, at a coil ratio of 1:1 as well as 0.46 V and 7.45 mA, respectively, at a coil ratio of 1:2.

VI. CONCLUSION

The experimental results of this study revealed that the performance of a flat transformer is mainly influenced by the tightness of the fitting between the primary and secondary coils and not by the magnetic material between the coils. When the primary and secondary coils of the transformer developed in this study had a tight fitting without any spacer material, the secondary coils induced the highest voltage and current.

The material of the outer layers of the coils affected the transformer performance. The transformer performance in Setting E was superior to that in Setting C, which indicated that silicon steel serves as a key material and enhances the transformer performance.

The experimental results revealed that flat transformers' primary and secondary coils must be completely covered with magnetic materials. If any part of the coil is exposed, the transformer performance worsens.

The main limitation of this study was that experiments could not be conducted with different coil types because of the high costs of the coils. Manufacturing these coils entails a specific molding process, and the research team could not purchase enough coils at once to offset the process's cost. Consequently, each set of coils costs approximately US$1660.

The result of this research can be a flat transformer on automobile and electronic devices; it was light on that devices but remained limited to vertical height, and it was difficult to decrease vertical spaces.

This research could help minimize vertical height and flat power parts, including Consumer Electronics, or green energy electric vehicles, minimize vertical space of transformer block, and flat power supply model.

All cases show this design can amplify voltage but is different. Another is that this type of transformer can suit high-frequency voltage working conditions. But in this matter, there are not so many high-frequency working cases in power supply location, it more suitable in signal transfer, but if use silicon steel the transformer look suitable both low frequency and high-frequency cases, it may be suitable transfer power and signal at one transformer, it is an inter-

esting idea.

Transfer effect is another obvious research title, input 11Vac, but only not 1Volt output, it very bad of effect, a reason maybe causes by magnet force curve leak outside and silicon or magnet, not enough thickness, but this not sure, this is another optimization study topic in the future, this time a prototype still need do more optimization.

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