High Frequency Inductive Power Transfer Device for Ultrasonic Applications

Nikolay Dimitrov Madzharov

Abstract-**High Frequency Inductive Power Transfer (HFIPT) device is inherently a transformer, which transfers high frequency electrical energy from the primary to the secondary without direct contact between the two components. The difference between the HFIPT device and standard transformers is in the fact that the secondary of the transformer moves at a relatively high speed. This paper contains the development results of linear HFIPT for ultrasonic applications. There are several significant factors that make design of HFIPT more challenging. Due to complicated circuit of different ultrasonic applications where the compact transducer (CT) impedance could be change strongly in the technological process, there must be compensating capacitors installed in the primary and secondary circuit.**

Keywords - **HFIPT, MDM, CT, Matchingcircuit, Air gap.**

I. Introduction

HFIPT to a moving recipient is not common in the field of electrical engineering; however, some systems have been developed in the past for special situations. An early example of this was an HFIPTsystem invented in St. Petersburg, Russia around 1940 for a vehicle receiving energy inductively from two cables. The vehicle had an "antenna" on the bottom with a rectifier and DC motor. Later, similar devices were used in coal mines with explosive atmosphere. The frequency of the current used in these systems was several kilohertz. Contactless power transfer allows avoiding problems caused by currently used sliding contacts. Sliding contacts have insufficient life time due to mechanical wearing and electro-chemical degradation in the process of service [1-5].

The HFIPT device is inherently a transformer, which transfers electrical energy from the primary to the secondary without direct contact between the two components. The difference between the HFIPT device and standard transformers is in the fact that at least the secondary of the transformer must move at a relatively high velocity. In order to have good operating mode of the US generator and sufficient technological results a special matching circuit has to be developed.

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II. Magnetic Materials for HFIPT Cores

There are two families of materials for the HFIPT primary and secondary magnetic core, ferrites and Magneto-Dielectric Materials (MDM).Selection of material must be based on mechanical properties, permeability, electric conductivity, losses and electrical strength. Ferrites of Mn-Zn type can't be used for HFIPT because of low resistivity and electric strength. Ni-Zn or special ferrites may be theoretically used for these applications. However the inverted E shape of the primary magnetic core used for the HFIPT device is not a standard shape available for ferrites. Therefore, in order to make the core using ferrites, ferrite plates must be machined, custom manufactured in net shape or the cross-section must be made by combination of several pieces. "Net-shape" manufacturing of large ferrite cores is expensive and anyway they must be machined to the final tolerances; machining of ferrites is very difficult and expensive requiring special tools. It is almost impossible to make technological holes in the core for HFIPT assembling. If the ferrite cores were made from multiple pieces, then a support structure would be required requiring additional costs and space. Plus, multiple assembling gaps in the core will results in reduction of equivalent permeability of the core.Results of a search for magnetic materials that could be used for HFIPT core are presented in table 1.

Table I
Magnetic Materials for HFIPT

Material	Permea-bility	El. Re-sistivity Ohm.cm	El.StrengthVrms/mm (300kHz)	Availabili-ty in sizes and shapes	Curie temp. ^0C	Thermal conduct. W/cm^2
Mn-Zn Ferrite	750-15000	Low 10-1000	Low	TBD	100-300	0.03
Ni-Zn Ferrites	10-2000	High	High TBD	TBD	150-450	0.03
Fer. 559	18-20	High >15000	Medium ≤100	Any when machined	>300	0.04
Fer.119	7	Very High	> 300 Vrms/mm	Any when machined	>300	0.02
Fluxtrol 50	50	Low	< 100 Vrms/mm	Any when machined	>300	0.05
Fluxtrol HF	5	Very High	>> 300 Vrms/mm	Any when machined	>300	TBD

MDMs are manufactured in large standard sizes and are easily machinable with standard tools. Because of that, it is possible to make the primary magnetic core out of 1 piece of material, eliminating the need for any joining or support structures. Therefore, MDMs are the preferred material for constructing the geometry. Four MDMs are presented in Table 1 – Ferrotron 559, Ferrotron 119, Fluxtrol 50 and new HF material Fluxtrol HF. Fluxtrol HF has excellent mechanical properties, good electrical strength and low losses but its permeability is insufficient for effective use in HFIPT [6].

For HFIPT cores material Fluxtrol 50 was chosen and tested. It has relatively high permeability, excellent mechanical and electrical properties and may be machined into any shape with high precision.

III. HFIPT DESIGN

Two major criteria must govern optimal HFIPT design:

A. Good controllability based on relation between primary and secondary currents;

B. Minimal apparent power on HFIPT input resulting in less losses, smaller step-down transformer (SDT) and smaller capacitor battery at the generator output [3,4].

For criterion A. Impedance Z_{P0}(see fig. 4) of coupling must be as small as possible. With a very small Z_{P0}, the same current will flow in the load and at the HFIPT input.

For criterion B. There are optimal values of HFIPT components, that must be defined with account of restrictions set by the device size and material properties. It is clear that optimal design depends on parameters of the load. CT is a complex resonant load and its equivalent impedance depends strongly on frequency and to a certain degree on a signal level. For these reasons it is difficult to rely on calculation of CT impedance starting from its equivalent resonant scheme.

Additionally, it was found from calculations and open circuit tests that the HFIPT magnetization current has a significantly high value (about 120 A). There are three options to reduce the magnetization current:

1. Increase the number of primary turns.
2. Make the active zone (length of the secondary block) longer.
3. Provide larger area for magnetic flux to cross the gap using deeper grooves or multiple grooves, which might be easily accomplished using MDM materials.

In order to reduce HFIPT losses, the following methods are possible:

- use litz for the primary. However, this will lead to more complicated design. At frequency 28 kHz the penetration depth in copper equals to 0.4 mm and litz AWG 38 may be used.
- optimal design of primary with wider current carrying surface.
- core design optimization to improve magnetic coupling and therefore to reduce magnetization current.

The developed design (see figure 1) is similar to the Flat Core to E-shaped Core, except that the secondary E-shaped Core poles are "dropped into" the primary magnetic circuit. The main advantage of this design compared to the Flat Core to E-shaped Core is that the magnetization current should be less, because there is a longer magnetic coupling zone between the primary and the secondary magnetic circuits. Another advantage is that the sensitivity to the gap variation is much lower than with the Flat core for the primary. The disadvantage of this style is that there is less space available for copper if there is a limit on the height of the secondary.

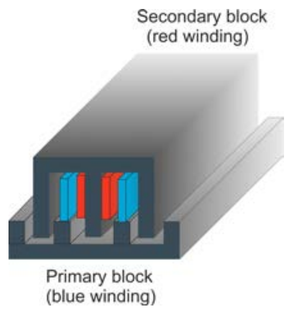

Fig. 1. HFIPT design of an Inverted E-shaped Core to E-shaped Core

Specifications the designed HFIPT are: input power3 kW; work frequency25 – 35 kHz;max. output voltage, amplitude - 1000 V ; stable operation with gap variation in a range 3 +/- 0.5 mm; efficiency> 90 % ; air natural cooling.

Figure 2 shows dimensions of the HFIPT device mock-up.The secondary core width is 62 mm, height is 42 mm and the length is 50.8 mm according to standard thickness of Fluxtrol blocks. The primary core width is 80 mm and the overall HFIPT length is 220 mm.

Primary winding W_1 has only one turn according to construction considerations and it is made of copper thickness 2.5 mm and height 15mm.

Secondary winding must be multiturn with W_2 more than 40 turns, which may be made of Litz AWG 38 (0.1 mm x 60, total cross section 0.47mm2).

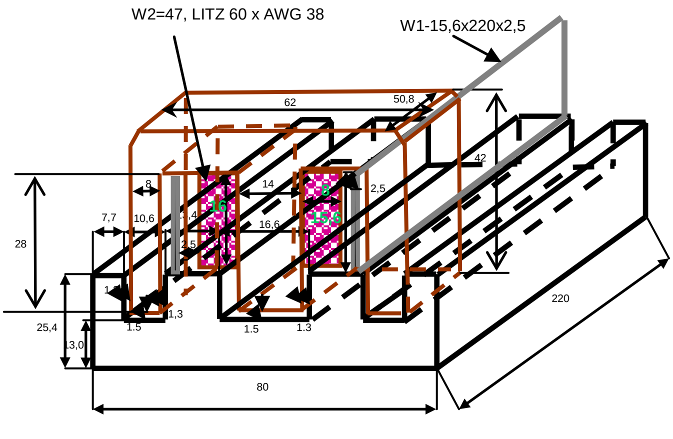

Fig. 2. Dimensions of HFIPT prototype with a multi-turn secondary winding.

The HFIPT magnetization current is equal to:

$$I_{MAG} = \frac{B.S_F}{n}(R_F + R_G) \tag{1}$$

$$R_G = \frac{l_G}{\mu_0.S_G} \tag{2}$$

$$R_F = \frac{l_F}{\mu.S_G} \tag{3}$$

where S_F, S_G – cross-sectional core and air gap area ; n – turn number; R_F and R_G – core and air gap reluctance; l_F and l_G - magnetic path and air gap length.

Voltage per turn is equal to

$$U = 2.\pi.f.B.S_F \tag{4}$$

For selected induction of 0.25T (RMS) the voltage per turn is 21V (RMS).

IV. DESIGN OF HFIPT MATCHING CIRCUITRY

An initial configuration of the circuitry is shown in Fig.3. It contains a US load with parallel capacitor battery in the secondary circuit - CT, HFIPT and matching block on the primary side. Matching block, contained matching transformer and parallel capacitor battery. It is essential to select an optimal scheme for the reactive power compensation. Number of turns of the secondary winding must be defined according to a CT parameters. Profound study of HFIPT and component performance was made using computer simulation, experimental study and combination of both [1,7,8].

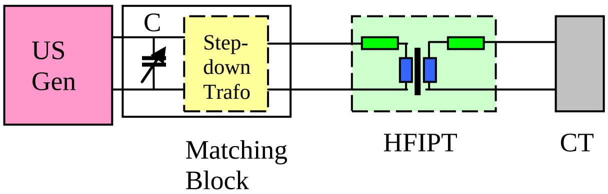

Fig. 3. Initial configuration of HF IPT and matching circuitry

The studied circuit is shown in Fig.4. As mentioned earlier, a SDT may be made with a good magnetic circuit and relatively low stray inductance. In the first approach it may be considered as ideal and therefore excluded from consideration. HFIPT must be considered as a "bad" transformer with a gap in magnetic circuit and big stray inductance of windings especially of the primary one due to significant inductance of rails.

A. Π-parameters of HFIPT and "IDEAL" Compensation Capacitances

The whole circuit "HFIPT + SDT" with linear parameters may be accurately described as a passive 4-pole and represented in the form of T or Π schemes. These parameters are very important for the HFIPT design and performance evaluation. If the ratio of SDT is the same as of HFIPT, it is not necessary to "transfer" the CT parameters on the generator side and all the differences in values are due to the influence of SDT and HFIPT. Parameters of SDT + UIPT are given below for winding ratio 47:1:1:47 for HFIPT gaps from 0,5mm to 3mm as well as the capacitor values necessary for complete compensation (Fig. 4).

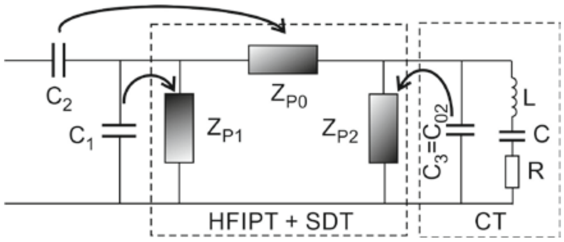

Fig. 4. "Π" parameters of "HFIPT + SDT" and their compensation elements

B. Determining the "Π" Parameters

The parameters of these schemes may be found from 3 independent measurements on output and input of the 4-pole. In turn these measurements may be performed using AC impedance meter such as LCR or method of voltmeter and ampermeter. In the last case a phase angle must be also found for accurate calculation. The HFIPT + SDT circuit has high quality factor and for matching purposes it is sufficient to measure *U* and *I* only.

The procedure for determining the "Π" parameters includes measuring the following impedances:

Z_{OC1} – impedance measured on primary with open circuit(OC) secondary

Z_{OC2} - impedance measured on secondary with OC primary

Z_{SC1} - impedance measured on primary with short circuit (SC) secondary

Z_{SC2} - impedance measured on secondary with SC primary

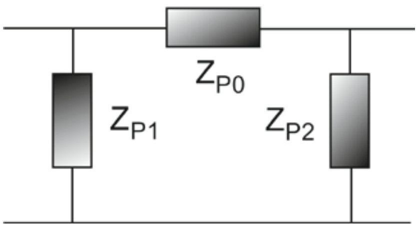

Fig. 5."Π" parameters of "UIPT + SDT"

As mentioned, it is enough to measure three regimes. The fourth measurement may be used for control of the measurement accuracy.

1. OC on the secondary

Z_{OC1} – impedance measured on primary with OC secondary

$$Z_{OC1}=U_{11}/I_{11} \tag{5}$$

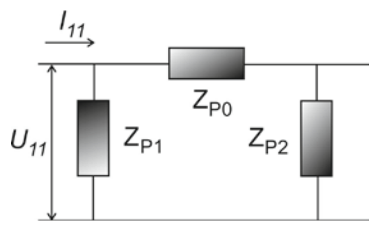

Fig. 6. Test on primary with OC secondary

2. Short circuit on the secondary.

Z_{SC1} - impedance measured on primary with SC secondary

$$Z_{SC1}=U_{12}/I_{12} \qquad (6)$$

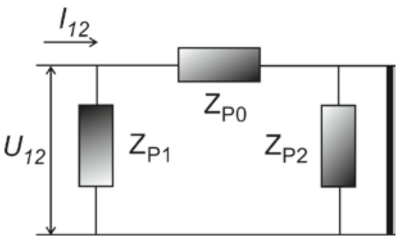

Fig. 7. Short circuit on the secondary

3. Open circuit on the primary

Z_{OC2} - impedance measured on the secondary with OC primary

$$Z_{OC2}= U_{23}/I_{23} \qquad (7)$$

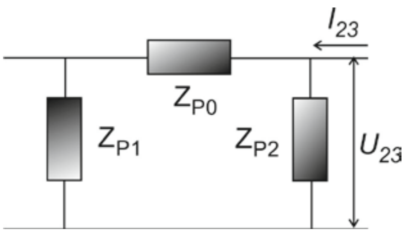

Fig. 8. Open circuit on the secondary

4. Short circuit on the primary

Z_{SC2} - impedance measured on the secondary with *SC* primary

$$Z_{SC2}=U_{24}/I_{24} \qquad (8)$$

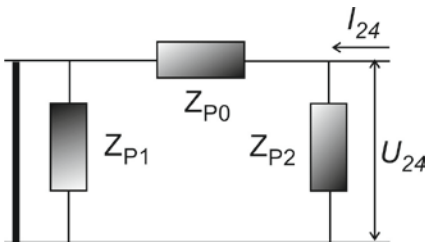

Fig. 9. Short circuit on the primary

Formulae for Z_{P1}, Z_{P0} and Z_{P2}:

$$(Z_{P0})^2= Z_{OC1}.\ (Z_{SC2})^2 / (Z_{OC2}-Z_{SC2}) \qquad (9)$$

$$Z_{P1}=Z_{P0}.\ Z_{SC1} / (Z_2-Z_{SC1}) \qquad (10)$$

$$Z_{P2}= Z_{P0}\ .\ Z_{SC2} / (Z_2-Z_{SC2}) \qquad (11)$$

Table 2 contains "Π" parameters of SDT+HFIPT with ratio 47:1:1:47 air gap from 0,5 mm to 3 mm and capacitors values necessary for their "ideal" compensation at frequency 28 kHz.

TABLE II
"Π" PARAMETERS OF THE SD+HFIPT 47:1:1:47 AND COMPENSATING CAPACITORS

Gap, mm	Z_{P1}, Ohm	L_1, mH	C_1, nF	Z_{P2}, Ohm	L_2, mH	C_2, nF	Z_{P3}, Ohm	L_3, mH	C_3, nF
0,5	1522	8.65	3,7	137.3	0.78	40	283.6	1.61	19,4
1	1508	8.57	3,67	134.2	0.76	41	278.0	1.58	19,7
1,5	1603	9.12	3,4	133.7	0.76	41	270.9	1.54	20,2
2	1614	9.18	3,4	130.8	0.74	42	251.3	1.42	21,8
2,5	1652	9.40	3,3	130.6	0.74	42	246.5	1.40	22,2
3	1659	9.43	3,3	130.5	0.74	42	237.5	1.35	23,1

Analysis:
1. Values of capacitance C_3 resonant with L_3 at 28 kHz is close to the natural value of the CT parallel capacitance C_0 for turn numbers 47.
2. Variation of the resonant C_3 is about -4/+10% when the coupling gap changes in a range 1.5 ±1.0 mm
3. It follows from the table that HFIPT scheme parameters change around +/-10% when the gap varies in the range from 0 to 3 mm. Besides of parallel capacitor C_1, this scheme contains an additional series capacitor C_2 in the primary side, which may be also used for matching or regime stability adjustment if required.
4. Analyzing the "Π" equivalent parameters of the HFIPT (Figure 4) it was found that the value of Z_{P0} was small. Hence, the capacitor C_2 must be big and does not influence matching essentially.

V. EVALUATION OF HFIPT LOSSES

In order to make a full evaluation of the HFIPT losses, a temperature test was implemented. Figure 10 shows the temperature of the HFIPT secondary core vs time. During the tests HFIPT secondary was covered with thermal insulation.

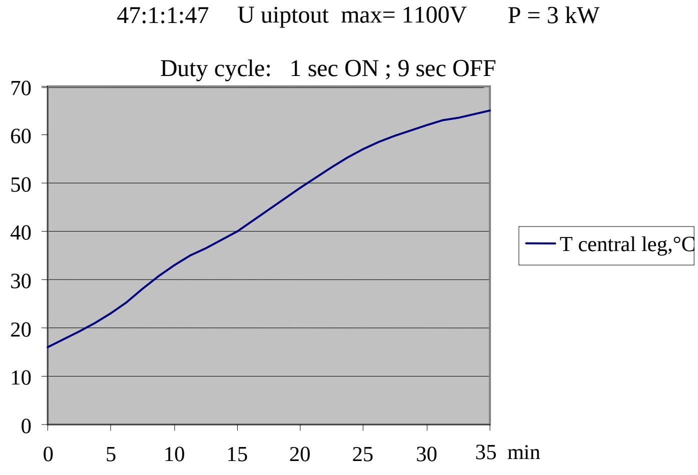

Fig. 10. HFIPT secondary core temperature vs time at ratio

Value of ratio (ΔTemp/Δtime) and losses ΔP have been determined from Figure10 by the following formula:

$$\Delta P = \frac{c.G.\Delta T}{\Delta t} \quad , \qquad (12)$$

c – specific heat of Fluxtrol, 0.444 J/g^{0}C
G – component mass, g
Δ T – temperature differential
Δ t – heating time differential.

The tests and calculations for power losses in HFIPT secondary core : G = 500 g; Δ t – 2100 sec at duty cycle 10 %,

showed for 47:1:1:47 - ΔP= 51,8 W;

The total power losses in primary and secondary FL core + losses in primary and secondary winding are close to 136 W at input power of 3 kW. The obtained results give an efficiency of 93 % - 95 %.

VI. CONCLUSION

The presented a profound theoretical and experimental study of the most prospective geometrical solutions and designs for an HFIPT established a basis for development of HFIPT. The analysis showed that the most favorable solution is an inverted E-shaped primary magnetic circuit with popped-up single-turn winding and an E-shaped secondary magnetic circuit with multi-turn Litz winding.

A method for predicting the HFIPT matching performance with any load has been developed. Using this method, it is possible to determine the parameters of an electrical circuit (losses, apparent power, currents and voltages) as well as parameters of the resonant circuit composed of capacitor battery, transformer and HFIPT.The HFIPT was able to be matched to the US generator at rated power without changing the ratio of the trafo or the value of capacitance for gaps between 0 and 3 mm. The stability of electrical parameters was very good in this range of gaps.

The final electrical and thermal tests showed that the efficiency of HFIPT with ratio 47:1:1:47 is 93-95% which is good for such system. After 35 min at full power and duty cycle of 10% the temperature of HFIPT secondary core reached 70 °C, which is acceptable for the used materials.

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