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Design and analysis of contactless transformer using series resonant converter

***Abstract**. A loosely contactless transformer with a large air gap has small magnetizing inductance and large leakage inductance comparing with a closely conventional transformer. This paper focus on analysis, design and measurement results of the loosely winding contactless transformer using resonant converter. Finally, the experimental set up is built to transfer power of 300 W over the different gap variation (1mm-10mm) using series resonant converter. On the contrary to the traditional closely coupled transformer, the contactless transformer with separated primary and secondary winding is used.*

***Streszczenie.** W artykule przedstawiono wyniki projektu i analizy transformatora o luźnym uzwojeniu do przesyłu bezstykowego z wykorzystaniem przekształtnika rezonansowego. Badania eksperymentalne polegały na przesyle 300W energii przy różnych rozmiarach szczeliny powietrznej transformatora. (**Projekt i analiza bezstykowego transformatora z wykorzystaniem przekształtnika rezonansowego**).*

Keywords: Contactless transformer, resonant converter, contactless power transfer
Słowa kluczowe: transformator bezstykowy, przekształtnik rezonansowy, bezstykowy przesył energii.

Introduction

Nowadays, contactless power transfer are developed and investigated widely [1-3]. Contactless power transfer using inductive coupling without a mechanical contact has the advantages of electrical isolation, safety, low maintenance, reliability, robustness and a long-product life. It will play a vital role in future of power transfer of energy which does not require a mechanical contact with supply energy. The potential application of contactless power transfer can range from power transfer to low power home appliances to high power industrial systems. The prospective candidates for use of this technology is like medical, marine, transportation and battery charging applications where physical connections either dangerous or inconvenient. Beside, for power supplies in harsh environments such as outdoor lighting and mining the electric isolation is essential.

In conventional application, a transformer used for galvanic insulation between the source and load. It was based on closely winding with high magnetic coupling coefficient between the primary and secondary winding.The contactless transformer is a loosely winding transformer with separated primary and secondary windings. Since the two windings of the transformer are physically separated by an air gap, this air gap bring to a low coupling efficient and high leakage inductance which results in a poor power conversion [1, 4]. In order to minimize converter switching losses and to compensate for the high leakage inductance of the transformer, the compensation capacitors are used in contactless power transfers applications [5, 6].

This paper begins by discussing the principles of series resonant converter. Following this, design and analysis of the contactless transformer is discussed. Then, an experimental comparison between different gaps is done in order to validate the design and analytical calculation of the loosely winding transformer.

The principles of series resonant converter with contactless transformer

Fig.1 represents a dc-dc full bridge converter using a contactless transformer. The high frequency power inverter transfers the input power to the load through a loosely coupling contactless transformer, a series resonant compensation and rectifier. As shown in the Fig.2, the relationship between switching frequency (f_s) and resonant frequency (f_r) can be divided into three cases: $f_s < f_r$, $f_s = f_r$ and $f_s > f_r$. The converter operates in capacitive load mode where the phase angle of the inverter output current flowing in the resonant circuit leads the inverter output voltage when the switching frequency is below resonant ($f_s < f_r$).

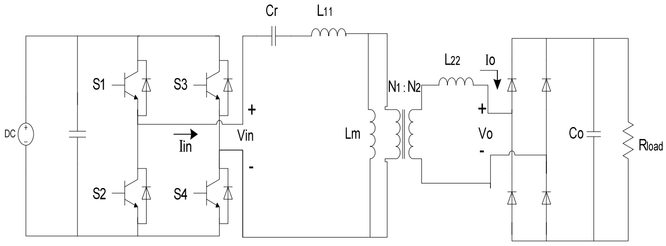

Fig.1. Series resonant converter

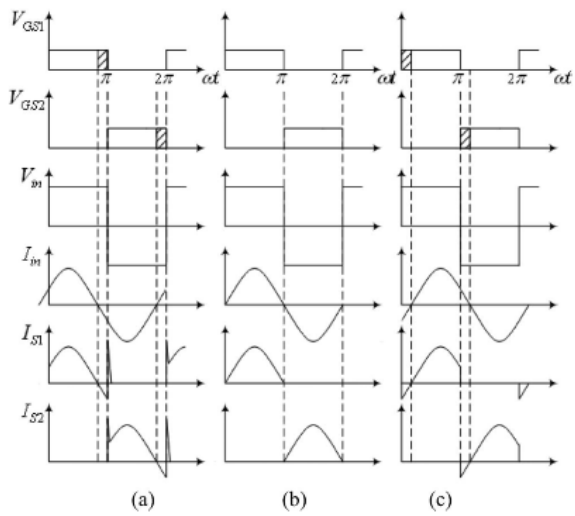

Fig.2. Resonant frequency characteristic waveforms with respect to switching and resonant frequency for (a) $f_s<f_r$ (b) $f_s=f_r$ (c) $f_s>f_r$ [7]

In this case, the anti-parallel diodes of the switching devices are forced to be turn off while conducting. Consequently, high reverse recovery current flows and the switching devices can be damaged.

When the switching frequency of the system equal to resonant frequency the converter ($f_s = f_r$) operates in resistive load mode where the phase angle of the inverter output current flowing in the resonant circuit is equal to the phase angle of the inverter output voltage. In this case, switching devices are turned off at zero current which reduces switching losses and high efficiency can be achieved. But, since the air gap of the contactless transformer varies, it is difficult to keep the switching frequency equal to the resonant frequency ($f_s = f_r$). In the case of the switching frequency higher than resonant frequency ($f_s > f_r$), the converter operates in inductive load mode where the phase angle of the inverter output current flowing in the resonant circuit lags the inverter output voltage. In this case, no turn-on losses of the switching devices are produced and turn-off losses can be reduced by applying shunt capacitor. So, in the system of experiment, the switching frequency is set to be equal to the resonant frequency.

Design and analysis of the contactless transformer

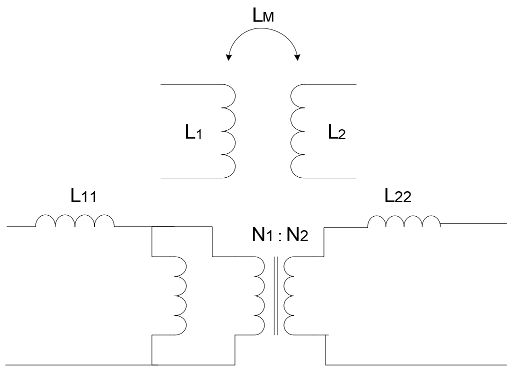

Fig.3. An Equivalent circuit of the contactless transformer

Ferrites are the most common types of material used for magnetic cores in contactless power transfer applications. In this design of the loosely winding transformer, soft ferrites type 3C94 from Ferroxcube which has low losses even operates high flux densities is used. The number of windings is equal to 16 turns, and a 1:1 turns ratio is obtained using EE cores. Fig.3 shows an equivalent circuit model of contactless transformer. The equivalent circuit consists of primary side leakage inductance (L_{11}), secondary leakage inductance (L_{22}) and magnetizing inductance (L_m). The equation between winding ratio (N_1/N_2), magnetizing inductance (L_m), leakage inductance (L_{11}, L_{22}), self inductance (L_1, L_2), mutual inductance (M) and coupling coefficient (K) is respectively

(1) $$M = L_m\left(\frac{N_2}{N_1}\right)$$

(2) $$k = \frac{M}{\sqrt{L_1 L_2}}$$

(3) $$L_{11} = L_1 - L_m$$

(4) $$L_{22} = L_2 - L_m\left(\frac{N_2}{N_1}\right)$$

(5) $$L_{ser} = L_1 + L_2 + 2M$$

(6) $$L_{par} = L_1 + L_2 - 2M$$

An impedance analyzer (LCR meter) is used to measure primary and secondary side self inductance (L_1, L_2), series inductance (L_{ser}) and parallel inductance (L_{par}). The measured value of equation (5) and (6) is used to determine the mutual inductance, M using equation (7).The reactance of a transformer can be determined from open-circuit and short-circuit measurement [8].

(7) $$M = \frac{|L_{ser} - L_{par}|}{4}$$

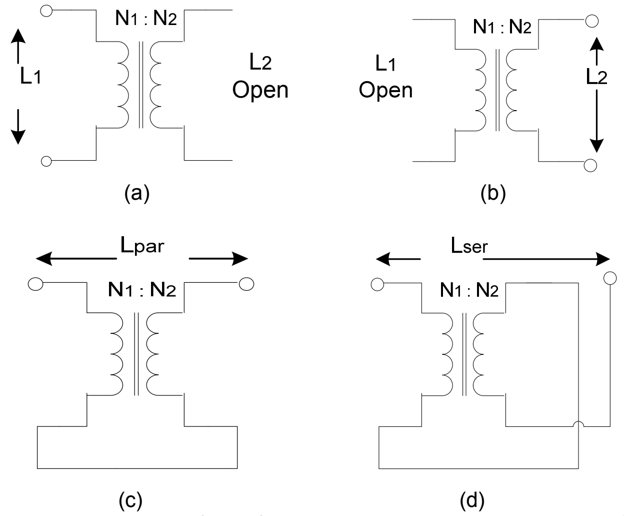

Fig.4. Measurement of transformer parameters, (a) primary side self-inductance, (b) secondary side self-inductance, (c) parallel inductance, (d) series inductance.

The values of mutual and self inductances of the contactless transformer depends on several parameters such as the gap length between the cores, core sizes and material permeability, and the turns number of primary and secondary windings. In a high-frequency converter, phenomena such as the skin and proximity effects need to be consider. The efficiency also depends on winding resistance due to the high magnetizing current of transformer [9].

The voltage gain of the transformer is affected by the circuit parameters such as magnetizing inductance and leakage inductances. In order to increase the transformer voltage gain, the leakage inductances (L_{11}, L_{22}) have to be reduced and at the same time increasing the coupling coefficient. Table 1 shows the measured parameters of the contactless transformer of EE type core. The measured results show that the coupling coefficient of the EE core largely drops as air gap increase between 0.749 to 0.29 for gap between 2mm to 10mm.

Table 1. The measured parameters of the contactless transformer with variable of air gap

Parameters	2mm	4mm	6mm	8mm	10mm
L_1 (µH)	141.32	102.5	85	49.87	42.2
L_2 (µH)	124.3	91.4	71.2	47.41	30.22
L_m (µH)	99.32	61.83	43.73	23.93	10.4
L_{11}(µH)	42	40.67	41.25	25.94	31.8
L_{22} (µH)	31.03	29.57	27.48	21.47	19.82
K	0.749	0.64	0.562	0.492	0.29

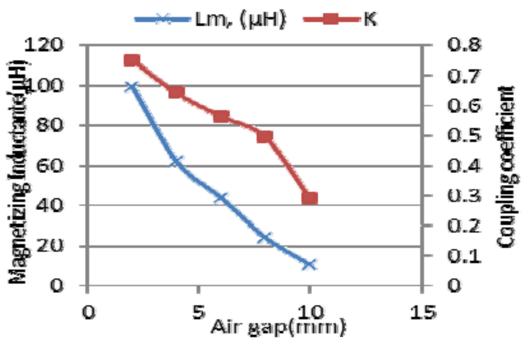

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Fig.5. Contactless transformer parameters according to the air gap variation

In the design of the contactless transformer, the coupled inductor model is used. It is necessary to calculate the value in the equivalent circuit as shown in Fig.6 to determine the characteristics of contactless transformer.

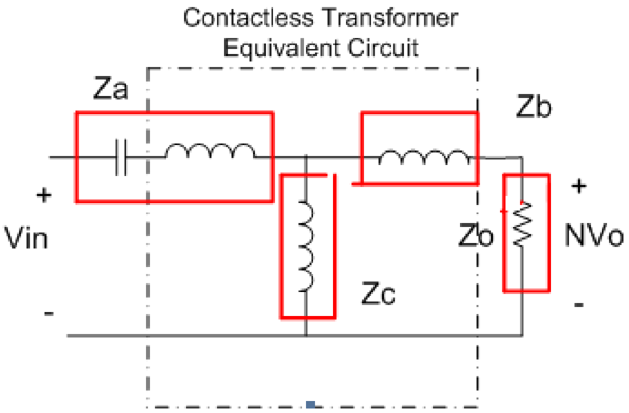

Fig.6. Equivalent circuit of the contactless transformer

From Fig.6, the voltage gain (G_V) and the current gain (G_I) between the input and the output of the contactless transformer are calculated analytically.

(8)
$$G_V = \frac{V_o}{V_{in}} = \frac{1}{N}\frac{1}{1+\frac{Z_a+Z_b}{Z_o}+\frac{Z_a(Z_b+Z_o)}{Z_cZ_o}}$$

(9)
$$G_I = \frac{I_o}{I_{in}} = N.\frac{1}{1+\frac{Z_b+Z_o}{Z_c}}$$

where

$$N = \frac{N_1}{N_2}$$

$$Z_a = j\omega L_{11} + \frac{1}{j\omega C_r}, \quad Z_b = j\omega N^2 L_{22},$$

$$Z_c = j\omega L_m, \quad Z_o = N^2 R_{eq}, \quad R_{eq} = \frac{8R_{load}}{\pi^2}$$

C_r is a series resonant capacitor which allows a compensation of the reactive part . The rectifier circuit and the capacitor filter of the secondary side can be represented as ac equivalent load resistance which equal to R_{eq} [10] . The resonant condition is achieved when the primary leakage inductance (L_{11}) of contactless transformer was compesated by resonant capacitor . The resonant frequency is obtained by using equation

(10)
$$L_{eq} = \frac{L_m L_{22} N^2}{L_m + L_{22}N^2} + L_{11}$$

(11)
$$f_r = \frac{1}{2\pi\sqrt{L_{eq}C_r}}$$

Leq is an equivalent inductance when the secondary side of the transformer is in short.

Experimental results

The experimental set up is designed with 50Vdc input, 50 kHz switching frequency, 10 Ω load resistance and a 0.2 µF capacitor as resonant capacitor. The following figure of 7, 8, 9 show the waveforms of the transformer primary side voltage (V_{in}) and current (I_{in}) and the transformer secondary side voltage (V_o) and current (I_o) respect to the gap variation for 4mm, 8mm and 10mm.

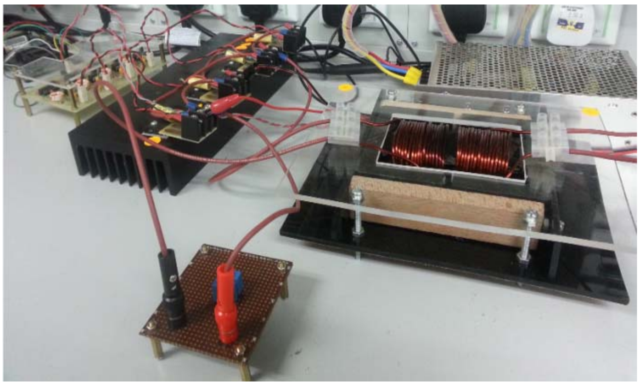

Fig.7. Experimental set up

Table 2. Experimental rms values of transformer primary side voltage (V_{in}), current (I_{in}) and secondary side voltage (V_o), current (I_o)

Air Gap	4mm	8mm	10mm
V_{in} (V)	49.2	48.4	47.2
I_{in} (A)	4.95	5.4	5.11
V_o (V)	44.1	37.2	31
I_o	4.84	3.5	2.1

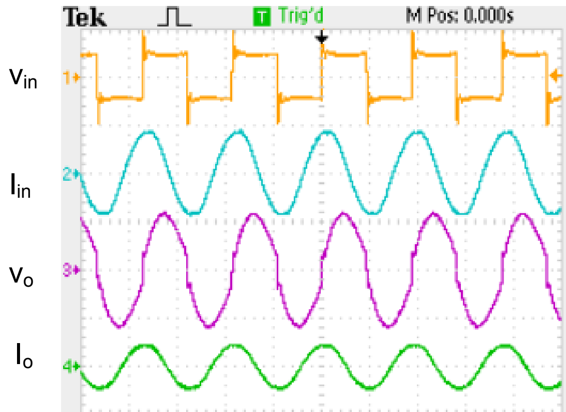

Fig.7. Experimental waveforms of the contactless system with 4mm gap [V_{in} = 100 V/div I_{in} = 10A/div V_o = 50V/div I_o =10A/div]

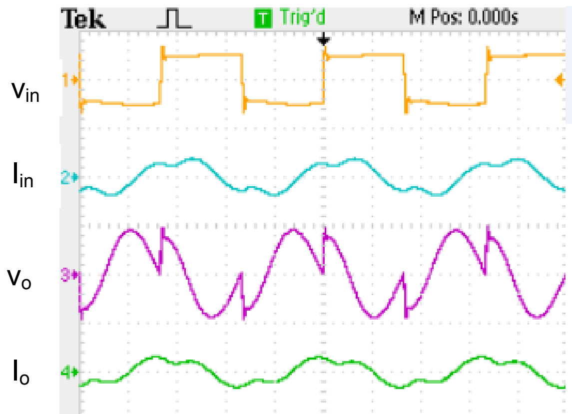

Fig.8. Experimental waveforms of the contactless system with 8mm gap [V_{in} = 100 V/div I_{in} = 10A/div V_o = 50V/div I_o =10A/div]

Table 2 shows RMS value of the inverter output voltage (V_{in}) and current (I_{in}) and the transformer secondary side voltage (V_o) and current (I_o) with respect to the air gap variation. The large leakage inductance and small magnetizing of the loosely coupled transformer made a large loss occurred in the system of the contactless transformer. The measured efficiency of the contactless transformer was 88% with 4 mm air gap, 50% with 8 mm air gap and 27% with 10 mm air gap. It shows when the gap was increasing the efficiency of system is low as large amount of primary current circulates through primary magnetizing inductances.

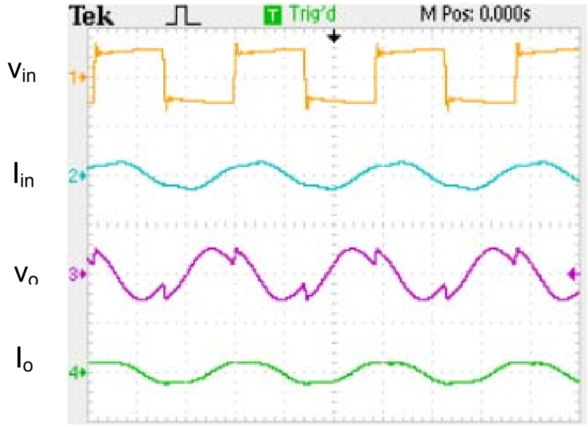

Fig.9. Experimental waveforms of the contactless system with 10 mm gap [V_{in} = 100 V/div I_{in} = 5A/div V_o = 50V/div I_o =5A/div]

Conclusion

In this paper, the electrical analysis characteristics of loosely transformer using coupled inductor theory and simplified models of the series resonant converter are presented. The experimental work is built to validate the theory with switching 50 kHz using 0.2μF resonant capacitor to compensate the high leakage inductance. The experimental have shown that contactless transformer with a series resonant converter can reduce the circulating current and improve the efficiency of system.

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