WIRELESS POWER TRANSMISSION VIA MAGNETIC RESONANCE AT VARIANT LOAD CONDITION

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Abstract— In this research, a magnetic resonant coupling wireless power transmission system is theoretically analyzed and simulated under different load conditions. The aim of this paper is to propose the use of a simple, cheap and easy technique for charging any mobile. The different technologies available so far for wireless transfer of electricity and the need for a wireless system of energy transmission are discussed here. The challenge is how to transfer power wirelessly without any bad effect on environment and human. The magnetic resonance concept for transmitting the power wirelessly for charging any mobile is being used in the core. To achieve maximum power transfer, an impedance compensating network can be used. The practical results are near to these obtained using the mathematical model and the theoretical calculations. The transmitting circuit is constant and receiving circuit is changeable. The load conditions making power efficiency at center frequency over 50 percents has been found out.

Keywords— *wireless power transfer technology (WPTT), capacitive power transfer (CPT), magnetic resonance*

I. Introduction

High power to moving objects can be supplied economically if appropriate wireless power transfer (WPT) sources exist. A maglev system, along with a linear synchronous motor, required primary windings transmitted along the track, results in increased construction and maintenance cost .

Placing windings on the moving objects along with a proper WPT system considerably reduces the cost. A suitable structure for high power WPT systems should be designed to satisfy the best performance and meeting the requirement of the application. The simplicity of the implementation is also essential in selecting the WPT structure.

In WPT for high power moving applications, the apparatus usually includes a small air gap along the main flux path that links two coils. A primary coil is placed on the stationary base unit while a secondary coil is on the vehicle. The latter coil effectively receives the power from the primary side through the air gap and delivers it to the vehicle. The power can be used immediately by a traction motors or can be stored for later use. Also, a WPT structure can be constructed in conjunction with a magnetic levitation system using Halbach arrays, permanent magnets (PMs) , passive and self-controlled systems.

Although the required power for a levitation system is usually lower than the power needed by a propulsion system, the combined system causes a reduction in total weight of vehicle and improves its performance.

Different WPT structures for transferring high power from long primary tracks to moving objects are considered. In particular, two types of WPT systems, i.e., with long bus bars and with long magnetic material cores are proposed. Also, WPT structures for monorail systems with U, S, E, Z and λ shapes are introduced. Two WPT structures are presented and analyzed for the linear servo motors.

A WPT system consisting of a U shape pickup on the vehicle and three wires as primary winding is designed for movable vehicles. The mentioned works not thoroughly discuss the system analysis and design, considering practical limitations such as operating frequency when both high power transfer and high efficiency are desirable. In order to attain high performances in WPT systems, capacitive compensations in both primary and secondary sides are recommended to provide resonance conditions.

Resonance based WPT systems save weight, space and cost of the system. However, some special applications can be supplied by non-resonance based WPT systems with proper designs. Coaxial WPT systems including a straight primary wire passing through the center of a cylindrical secondary core with an air gap have already been identified. It can be used in Maglev as well as in wireless EV charging systems and power delivery system for mining applications. Also a high power coaxial inductive power transfer pickup is presented. A partial design of the system is reported recently. However, a systematic modeling, analysis and design procedure is not reported in the literature. In this work, a coaxial WPT system as in Fig.1 is considered. A mathematical model is used for the system analysis including the compensating capacitors. The analysis includes the computation of transferred power, efficiency, coupling coefficient, etc. Then, a design procedure is proposed to achieve high efficiency and high transferred power. The work extends the implication of low power resonance based inductive magnetic coupling to high power applications like Maglev. The system parameters are obtained to meet the design specifications. Analytical results are verified by 3D FEM simulations to confirm the design.

ADVANTAGES

Implementation of this design for future electrification will bring a revolution in power distribution systems. Following points will justify the above statement.

1. Highly resonant strong coupling provides high efficiency over distance.

2. The power can be delivered in any direction i.e., Omni-directional.

3. Non-Radiative Energy Transfer is safe for the entire ecosystem.

4. Can reduce the manpower in installation of distribution system in the hilly areas as well as in the plain areas. As it is very difficult to electrify the hilly areas.

5. Transmission of power to remote areas such as islands, army bases, high altitude peaks, etc. is possible.

6. No need for meter rooms and electrical closets.

7. Reduction of e-waste by eliminating the need for power cords..

II. working methodology

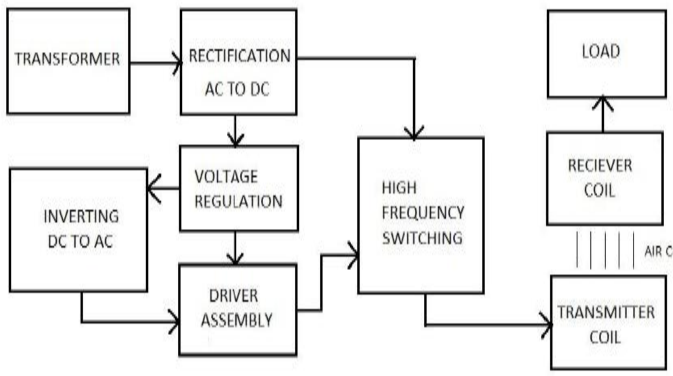


Fig 1: Block diagram of the carried experiment for a designing WPT system that explains the low to high frequency switching.

The design of this experiment includes the conversion of low frequency supply of 50 Hz to high frequency AC supply of 40 kHz. Then the converted supply is fed to the transmitter coil which is tuned to the same resonating frequency as that of the receiver coil. A high frequency oscillating current is induced in the receiver coil which is kept at a maximum distance of 35cm. The driving circuit for high frequency switching is based on the push-pull concept. The transmitter and receiver coils are made up of multi-strands litz wire of radius of 11cms and 15 turns.

A system consisting of four coils can be interpreted as an expansion of a transformer, which consists of two coils. First, we review the node equation of a transformer and then expand it.

A. Transformer

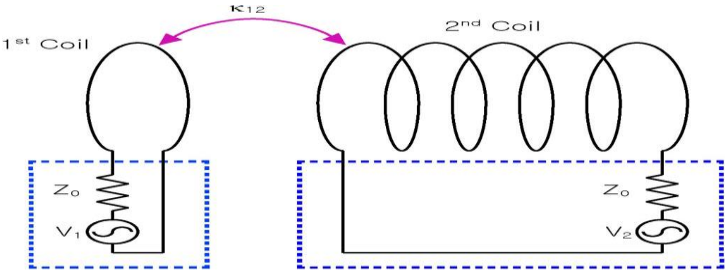


Fig2. Shows schematic diagram of two coils of a transformer.

The magnetic resonance can be best explained by the use of typical transformer . The coupling coefficient is k_{12}.

The mutual inductance can be given by :

$$M_{12}=k_{12}\sqrt{L_1L_2} \quad \text{……………………………(1)}$$

The nodal equations of the two coils are:

From primary side:

$$I_1 = \frac{V1}{Zo} + jwC_1V_1 + i_{L1} \text{…………………………(2)}$$

$$V_1 = jwL_1i_{L1} + jwM_{12}i_{L2} \text{………………………..(3)}$$

From secondary side :

$$0 = \frac{V2}{Zo} + jwC_2V_2 + i_{L2} \text{…………………………(4)}$$

$$V_2 = jwL_2i_{L2} + jwM_{12}i_{L2} \text{……………………..(5)}$$

k_{12} is the coupling coefficient, and M_{12} is the mutual inductance between the two coils. Z_0 is the characteristic impedance, which is normally 50 Ω. The resonance frequency of each coil is 1/√LC. The input impedance from the power generator can be calculated from (2) and (3).

$$\frac{1}{Zin} = \frac{i_1}{V_1} - \frac{1}{Z_0} = jwC_1 + \frac{1}{jwL_1 + \frac{w^2 M_{12}^2}{wL_2 + \left(\frac{1}{\frac{1}{Z_o} + jwC_2}\right)}} \text{… (6)}$$

Z_{1M} represents the contribution to V_2 due to the magnetic coupling and is expressed as

$$Z_{1M} = \frac{w^2 M_{12}{}^2}{jwL_2 + \frac{1}{\left(\frac{1}{Z_o} + jwC_2\right)}} = \frac{w^2 (M_{12})^2}{(Z_2)} = \frac{w^2 k_{12}{}^2 L_1 L_2}{Z_2} \text{….(7)}$$

Z_2 is the impedance of a closed loop at port-2. Frequency characteristic is not important for a transformer because the operating frequency is much lower than the resonance frequency. However, a wireless energy-transfer system using coupled magnetic resonance operates at near-resonance frequency, and the frequency dependence in (4) is important. If the two coils are identical, (6) is satisfied, i.e.,

$$w_o^2 L_1 C_1 = wo^2 L_2 C_2 = 1 = w_o^2 L_1 C_2 \text{ ……..(8)}$$

and the input impedance at resonance frequency is

$$Z_{in} = \frac{1}{jw_o C_1} // (jw_o L_1 + Z_1 M)$$

$$= \frac{1}{jwoC\ 1} // (jw_o L_1 (1 - k_{12}^2) + k_{12}^2 Z_o) \text{……(9)}$$

If the parasitic capacitance is negligible and K_{12} is unity, Z_{in} is exactly matched to Z_0, and the coupling efficiency becomes 100%. However, κ_{12} is decreased drastically when the distance is slightly increased, and Z_{in} deviates from Z_0. As a result, the coupling efficiency drastically decreases because of impedance mismatch. This is the main reason why long-distance power transmission is impossible in the case of a transformer. Although the operation frequency of an actual transformer is lower than the resonance frequency, this analysis can be helpful to understand why a magnetic-induction system does not have high coupling efficiency for midrange energy transfer.

We assume a lossless case for simplicity. The input impedance from the power generator could be obtained as was done in the previous analyses by calculating the mutual impedance successively from the output port.

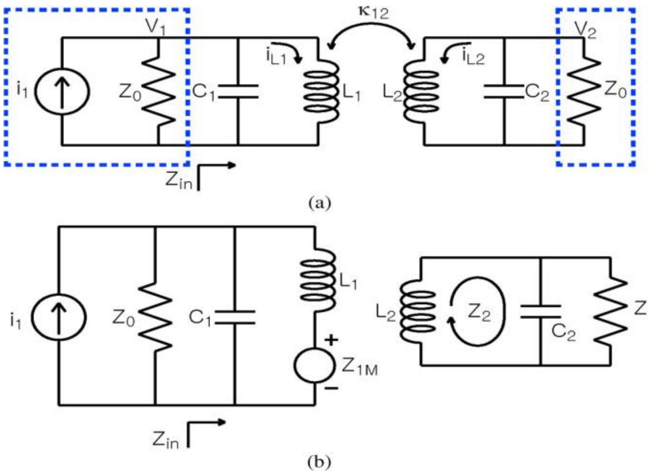
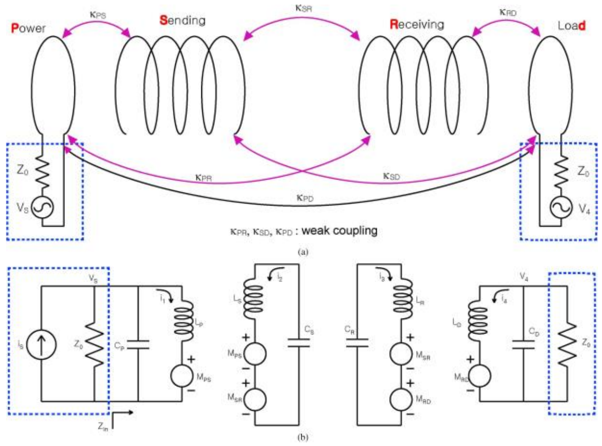


Fig. 3. (a) Circuit schematic for mutual inductance between two coils. (b).Circuit of (a) with compensation sources used to represent the effect of mutual inductance.



In Fig. 4, (a) Schematic of a wireless energy-transfer system using coupled magnetic resonances. (b) Circuit of (a) with compensation sources.

The mutual inductance Z_{RM} induced at the receiving coil by the load coil is

$$Z_{RM} = \frac{w^2 k^2_{RD} L_R L_D}{jw L_D + 1/\left(\frac{1}{Zo} + jw C_D\right)} = \frac{w^2 k^2_{RD}\ L_R L_D}{Z_o} \text{………..(10)}$$

the mutual inductance Z_{SM} induced at the sending coil by the receiving and load coils is

$$Z_{SM} = \frac{w^2 k_{SR}^2 L_S L_R}{Z_{RM} + jw L_R + (\frac{1}{jw C_R})} = \frac{w^2 k_{SR}^2 L_S L_R}{Z_R} \text{……………(11)}$$

the mutual inductance ZPM induced at the power coil by the sending, receiving, and load coils is

$$Z_{PM} = \frac{w^2 k_{PS}^2 L_P L_S}{Z_{SM} + jw L_S + (\frac{1}{jw C_S})} = \frac{w^2 k^2_{PS} L_P L_S}{Z_S} \text{……..…(12)}$$

Thus from equation (10), (11) and (12), we get ,

$$Z_{PM} = \frac{w^2 k_{PS}^2 L_P L_S}{jw L_S + \left(\frac{1}{jw C_S}\right) + (\frac{w^2 k_{SR}^2 L_S L_R}{jw L_R + \left(\frac{1}{jw C_R}\right) + \frac{w^2 k_{RD}^2 L_R L_D}{jw L_D + \left(\frac{1}{jw C_D} + \left(\frac{1}{Z_0}\right)\right)}}} \text{..(13)}$$

If the resonance frequency of the sending coil and of the receiving coil is same , then we have

$$w_o^2 L_s C_s = w_o^2 L_R C_R = 1 \text{………...(14)}$$

$$jwL_S + \frac{1}{jw\ C_S} = jwL_R + \frac{1}{jw\ C_R} = 0 \text{…………..…(15)}$$

At the resonant frequency , the impedance term of the capacitor and the inductor is zero. Hence Z_{PM} is reduced to

$$Z_{PM} = \frac{w_0^2 L_P L_D \frac{(K_{PS}K_{RD})^2}{K_{SR}}}{jw_0 L_D + \frac{1}{jw_0 C_D + \frac{1}{Z_0}}} \text{ …………….(16)}$$

Since equation (16) is very much similar to equation (7) of the two coil transformer, thus the two equation are same expect for the coupling constant .

Thus the simplified circuit can be constructed as shown in below figure

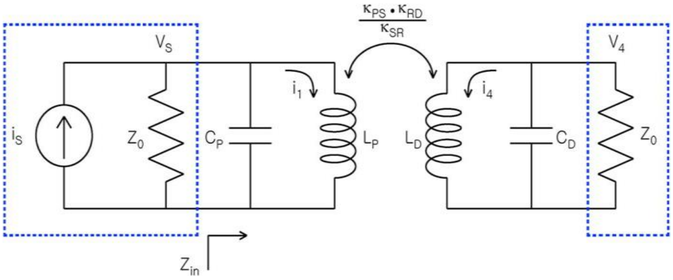


Fig 4. The above figure shows the simplified circuit at resonant frequency.

At resonant frequency we have,

$$w_O^2 L_P C_P = w_o^2 L_D C_D = w_o^2 L_P C_D = 1 \text{ ………..(17)}$$

$$Z_{PM} = \frac{w_0^2 L_P L_D \frac{(K_{PS}K_{RD})^2}{K_{SR}}}{jw_0 L_D + \frac{1}{jw_0 C_D + \frac{1}{Z_0}}} = -jw_o L_P + Z_o \text{……. (18)}$$

If

$$K_{PS}K_{RD}/K_{SR} = 1$$

Then,

$$Z_{in} = \frac{1}{jw_0 C_P} // (jw_0 L_P + Z_{PM}) = \frac{1}{jw_0 C_P} // Z_0 \text{ … (19)}$$

C_P is negligible, and Z_{in} is perfectly matched to Z_0. Theoretically, the coupling efficiency becomes 100%. Although KSR is small due to the long transfer distance, we can make $K_{PS}K_{RD}/K_{SR}$ into unity by adjusting the spacing between the power coil and sending coil or between the receiving and load coils. As a result, we can achieve high coupling efficiency”.

B. Coupled Transmission System

The WPT system includes power source which is a high speed switching circuit, primary impedance compensating network, two magnetically coupled coils, a secondary impedance compensating network, a high frequent rectifier, a voltage regulator and a DC load. The schematic diagram of WPT system is illustrated in Fig.1

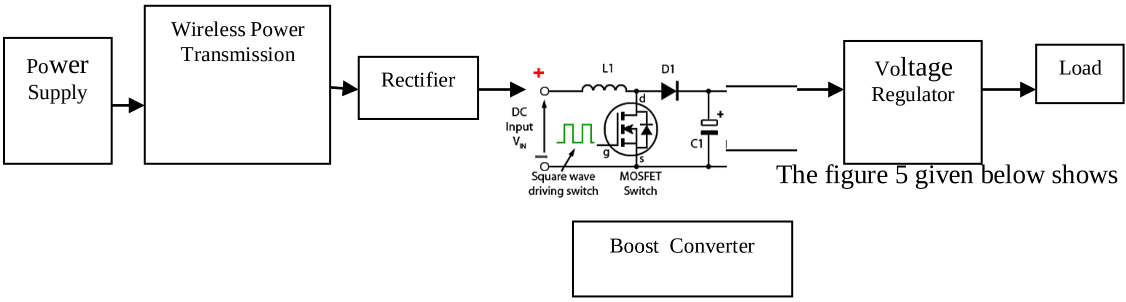
The high speed switching circuit is a single-ended high frequency quasi resonant inverter that consists of power MOSFETs along with triggering circuits. A power MOSFET (Metal Oxide Semiconductor Field Effect Transistor) is designed to handle large amount of power levels and can operate at high frequencies up to hundreds of kilo Hertz. Now, the development in power electronics reaches to a new power MOSFET (SiC MOSFET) that can operate at frequencies up to Mega Hertz which is used for high switching frequency applications.

The impedance compensating network (matching network) has a very important role in WPT system. It reduces the volt ampere rating of the power source by minimizing the reactance of input impedance and increase the power transfer efficiency by utilizing the magnetic field resonance.

From the primary coil, the time varying magnetic field is generated and gathered at the secondary coil for the transfer the average load power. A high frequency rectifier is widely used for the conversion of high frequency AC power into a DC power. There are two losses in contributions associated with the diodes in a high frequent rectifier; losses due to the forward conduction of the diodes and the high frequent loss according to the switching time of the diodes. These losses act as a result of the reverse recovery time of the diodes. To reduce and remove the effects of losses, Schottky diodes or ultrafast diodes are used in the rectifier circuit instead of normal diodes.

The voltage regulator is used to stabilize and control the DC voltage level according to the required load voltage. The load is generally an electrical load that consumes certain electric power. The mobile battery is a common load in a WPT system as charging a mobile wirelessly means no need to connect the mobile charger to a mobile phone physically. The mobile phone is put on the charging pad and the charging operation starts till the phone is fully charged. The transfer circuit is attached to the charging pad and the receiving circuit is inserted inside the mobile. The Wireless charging for a mobile via magnetic resonance is illustrated in Fig.6 given below.

The figure 5 given below shows overall transmission system.



III. Results and Discussions

The observations are tabulated. Based on the tabulation, the most efficient and reliable coil combinations were selected and wireless power transfer using magnetic resonance was accomplished and a mobile phone was charged for parallel resonance.

f = Frequency of oscillations, V1= DC Supply voltage, I1= DC current from SMPS, V2= Output voltage across load, I2= Output current, d= Normal distance between transmitter and receiver, dmax= Maximum normal distance between transmitter and receiver with output. For example, take an example using L1 as transmitter and L2 as receiver.

Operating frequencies varies from 10MHz to20MHz.

Optimum operating frequencies is found to be 13.8 MHz:

Table I	**VALUES USED TO EVALUATE SIMPLIFIED MODEL.**	
	Parameter	***Value***
1	Vs	200mV
2	gs,gl	1/300,1/300
3	Ct1,Ct2	180pF,180pF
4	L1,L2	756nH,756nH
5	g1,g2	2.878 × (10)^(-4)
6	K	0.33

The Table I shows the real circuit values for accurate analysis and simulation are obtained

A. Experimental evaluation

In Fig. 4, a standard transformer is used to supply Vs equal to 200mV to the whole WPT system on the left side. The voltage of the load resistance is detected by a voltmeter using probe on the right side. Frequency response of voltages as shown in Fig. 8 , and the working power efficiency is listed in Tables II.

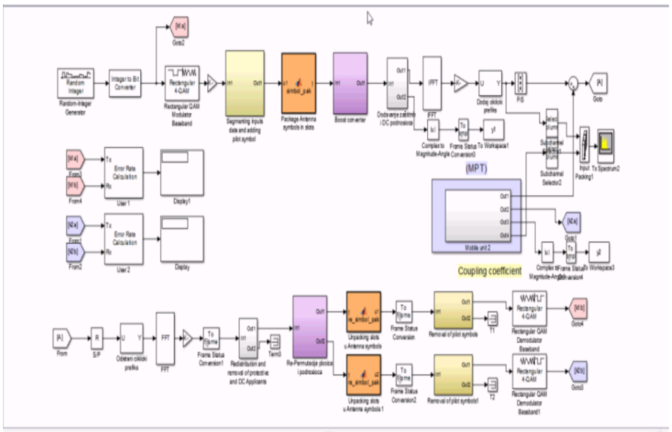


Fig 7. Simulation block diagram

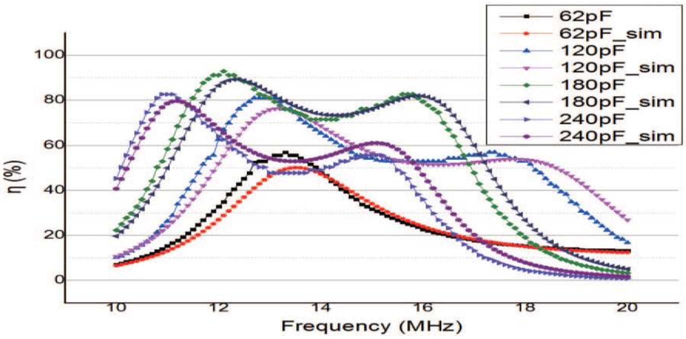


Fig 8. Frequency response of output voltages under different resonant capacitances

B. Results

TABLE II. SIMULATED AND MEASURED CENTER POWER EFFICIENCIES UNDER DIFFERENT CAPACITANCES

Capacitance (pF)	*Simulated n=0*	*Theoretical n=0*
62	47.73%	52.89%
120	72.4%	69.95%
180	75.53%	73.02%
240	52.89%	47.74%

- The simulation and experimental results are quite similar with the theoretical analysis above. It is complicated to analyze the resonance capacitance theoretically because the center angular frequency will be change with different load capacitance , accordingly we use simulation and experiment to demonstrate its assignable influence. In Fig. 8, when the resonance capacitance is smaller than primary capacitance, there exist only one hump frequency that permit maximum efficiency power transfer. As resonance capacitance gets larger and closer to primary capacitance, the one hump frequency separate to two hump frequencies and become more symmetric with respect to the center frequency.
- Meanwhile, frequency at trough point (lowest point between two peak points) becomes larger. If the resonance capacitance gets even larger, the two peak frequencies move farther and become asymmetric. The power efficiency at center frequency drops like shown in Table II.

IV. Conclusion

We have developed an equivalent-circuit model that can describe wireless energy-transfer systems via coupled magnetic resonances. Node equations for the resonance system were built with the method, expanding upon the equations for a transformer, and they were solved analytically for a lossless case. The solution shows that the transmission efficiency can be increased simply by adjusting the spacing between the power and the sending coils or between the receiving and the load coils. To consider a lossy system and calculate the frequency characteristics, an equivalent-circuit model was developed from the node equations and established in an electric-design automation tool. The parameters for the model were extracted, and simulation results were compared with measurement results. In this paper, we have investigated the magnetic-resonance system, and the developed model can be used to design wireless power-transmission systems.

The center frequency of receiving circuit changes as the resonant capacitance changes. The magnetic resonant coupling WPT system could achieve over 50% power efficiency at center frequency when the resonant capacitance is 62-240pF according to simulation and experiment. High efficiency can also be achieved in outrange resonant capacitance by using impedance matching .Comparing to the other load conditions, the coupling coefficient (distance) has more significant influence on power transmission efficiency.

Acknowledgment

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