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DESIGN OF INDUCTIVE POWER TRANSFER (IPT) FOR LOW-POWER APPLICATION

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ABSTRACT

Inductive power transfer (IPT) is preferred for numerous applications nowadays, ranging from microwatt bio-engineering devices to high power battery charging system. IPT system is based on the basic concept of electromagnetics induction which able to transfer the power from a source of electrical to the load without using any type of physical interconnection. This paper present a low-cost designed and implementation of IPT system via magnetic resonant coupling. NI Multisim 14.0 software was used to simulate the circuit diagram and the hardware prototype was developed for testing.

Keywords: inductive power transfer, track & pick-up, ni multisim.

INTRODUCTION

Inductive power transfer (IPT) [1] is a technology, which is now recognized as an efficient and acceptable technique for contactless power transfer across an air gap through weak magnetic coupling. As many industrial and domestic applications require power with no physical contacts, IPT is gaining global popularity and wide acceptance for numerous applications, as it offers the advantages of high efficiency, typically about 85–90%, robustness and high reliability in hostile environments being unaffected by dust or chemicals.

IPT systems are used in variety of industrial and consumer applications. Material handling systems, clean rooms, mobile device and battery charging, home appliances, biomedical implants circuitry, and charging of electric vehicles (EVs) can be considered as prime examples [2]–[9], [18-22]. Majority of these IPT powered applications require power flow in one direction and, consequently, most of the analysis, modeling, and design have been carried out in relation to unidirectional power flow of IPT systems.

Numerous IPT systems, with different circuit topologies and compensation techniques, have been proposed and successfully implemented in the past to cater for a variety of applications that range from low-power biomedical implants to high-power battery-charging systems in electric vehicles (EVs) [23]–[26].

In this paper, a low-cost IPT system was simulated and designed based on magnetics resonant coupling. The project consists of modeling and construction of the hardware to prove the feasibility of wireless power transfer. The simulation of the project has been done using NI Multisim 14.0 software. The purpose is to design the desired circuit in order to transfer power wirelessly.

INDUCTIVE POWER TRANSFER TECHNOLOGY

A typical IPT system as shown in Figure-1 consists of two physically detached subsystems with power transfer through induction. Typically, the system supplying the power is stationary and is named the primary, transmitter, or source. The system receiving the power is attached to a movable frame and is named the secondary, pickup, or receiver. The power is transferred via induction between two magnetically coupled coils, much like in a transformer. The coupling medium between the coils is air, which has a much higher magnetic reluctance than do the ferromagnetic materials used in transformers. As a result, the coupling coefficient [12] is in the range of 0.1-0.2 for stationary charging applications and less than 0.1 for midrange resonant applications. Therefore, these systems are usually referred to as loosely coupled systems to distinguish them from the tightly coupled transformer coils.

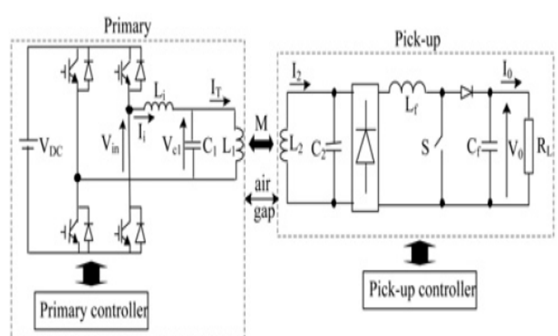

Figure-1. Typical IPT system [1].

Design and control of typical IPT systems have been well known and reported in literature [23]. IPT control technique with only a single controller [24] have been proposed and implemented in the past. The proposed technique is based on monitoring the variations in induced primary winding (L1) voltage and controls the primary current (I1) to regulate the amount of power transfer from the primary side to the load (pick-up).

Power-frequency droop characteristics [13] have been proposed to regulate the power flow in both directions without any additional communications link. The proposed controller is applicable to unidirectional as well as bidirectional IPT systems with either single or multiple loads. The controller ensures that power intake by the load side is always kept within the capability of the supply side.

Synchronization technique [14] has been proposed to control the power flow in BD-IPT system. To control the real power flow, the proposed system essentially requires synchronization between the voltage vectors, which are produced by both primary- and pick-up side converters. The technique uses an auxiliary winding, located on the pickup side, to produce a synchronizing signal without any RF communication. When the pickup converters are operated in synchronization with the primary, the amount and direction of power flow can be regulated by controlling magnitudes of and the phase difference between the primary and pickup voltage vectors.

Michael *et al*. [15] proposes a derivative-free optimization technique, based on genetic algorithm (GA), to determine the optimal parameters of PID controllers used in bidirectional IPT systems. In order to achieve desired power regulation performance, the controller has to meet many conflicting objectives. By judiciously selecting the objective function, which was a weighted combination of settling time, rise time, and peak overshoot (weighted objective), the parameters of PID controller have been determined using a multi- objective GA. These methods are simple to apply and can readily incorporate practical meaningful performance characteristics into the PID controller design and are not affected by the high-order nature of the system and fitness function.

Udaya *et al*. [16] proposes a novel current-sourced bidirectional IPT power interface, which is suitable for simultaneous contactless charging/discharging of multiple EVs or equipment. A converter or reversible rectifier, together with an inductor–capacitor–inductor (LCL) parallel resonant circuit, is employed in each EV or equipment to facilitate the controlled and bidirectional power flow between EVs or equipment and the grid. The proposed IPT interface is simple in design, implementation, and control, and it allows for modular operation to cater for high-power applications.

A novel multiple pick-up bidirectional inductive power transfer (IPT) system has been proposed in [28]. The proposed system uses a reversible rectifier on each side of the contactless IPT system to control both the amount and direction of power flow through phase modulation. The proposed concept is viable, and can be used in applications such as distributed generation to charge and discharge electric or hybrid vehicles, which serve as the means of mobility and energy storage.

A novel matrix converter [29] based IPT interface has been proposed to transfer power between EVs and grid. The proposed IPT grid interface utilizes a matrix converter to eliminate an additional low frequency power conversion stage. The system requires only a single-stage power conversion process to facilitate bi-directional and contactless power transfer between EVs and the grid. Without an additional power conversion stage, the IPT power interface is low in cost, and ideal for wireless charging and discharging of single or multiple EVs or V2G applications.

A new three-phase, high power bi-directional IPT system that can be used for rapid charging/discharging of EVs or V2G/G2V systems has been proposed in [28]. The proposed system uses a three-phase track, which is coupled to a three phase pick-up through weak magnetic coupling. Both track and pick-up are var compensated through an inductor-capacitor inductor (LCL) resonant circuit and driven by reversible rectifiers. The proposed three-phase IPT system is superior in performance and ideal for high power applications such as EVs, which require rapid charging.

DC IPT ANALYSIS FOR PICK-UP/ RECEIVER

In order to produce a valid dc equivalent, the resonant driven from an ac voltage source is replaced by an equivalent dc source and capacitor. This is achieved in a two-step process as showing Figure-2 .The first step a well-known Thevenin to Norton transformation is used to convert the ac voltage to an AC current source.

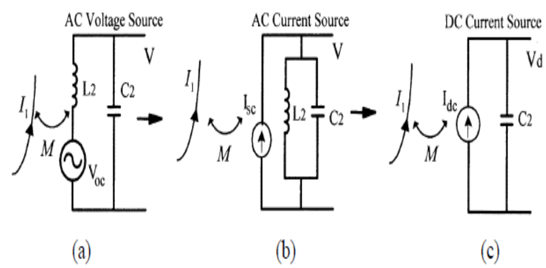

Figure-2. Equivalent ac and dc models of a parallel resonant tank [17].

The open circuit voltage of the pick-up is given by;

$$V_{oc} = jwMI_1 \quad (1)$$

M can be considered constant, and therefore the steady state value of is also essentially constant. The value of the AC current source in the Norton equivalent of Figure-2(b), is given by this voltage source limited by the impedance of the secondary winding. Thus;

$$I_{SC} = \frac{MI_1}{L_2} \quad (2)$$

For the second step shown in Fig. 2(c), the circuit of Fig. 2(b) is replaced by a dc current source shunted by a dc capacitor. The function of dc capacitor is to provide energy storage. The store energy in ac system is;

$$0.5CV^2 + 0.5LI^2 = 0.5CV_p^2 \quad (3)$$

Where V_p is the peak capacitor voltage, The DC energy stored is $0.5CV_d^2$ where V_d is the dc voltage across the capacitor. For equality therefore, $V_d = V_p$.

Similarly in the ac system with perfect tuning the power flow to the energy store is $\frac{I_{SC}V_p}{\sqrt{2}}$ (ignoring the fluctuating power flow at double frequency). The current in the DC circuit is equal to;

$$I_{dc} = \frac{MI_1}{\sqrt{2}L_2} = \frac{I_{sc}}{\sqrt{2}} \quad (4)$$

So that for equality of power flows in dc circuit;

$$I_{dc}V_d \quad (5)$$

The resonant tank of a typical IPT system operates between 10–50 kHz, thus a dc model of the peak voltage envelope is sufficiently accurate for control purposes provided the bandwidth of the designed controller is constrained such that it is not affected by the resonance currents.

RESONANCE MODEL CALCULATION

Resonant coupling is a phenomenon whereby two similar frequency resonant objects tend to couple, while interacting weakly with other off resonant environmental objects. Therefore, the resonant frequencies of the transmitting element and the receiving element are the most important parameters in wireless power transmission.

The resonant frequencies of both the transmitting and receiving coils can be obtained through the calculation of inductance of a circular coil, resistance of the winding , resonant frequency, capacitive reactance and inductive reactance. The inductance of a circular coil is obtained directly by the following formula;

$$L = N^2 \mu_o r\left(\ln\left(\frac{8r}{a}\right) - 1.75\right) \quad (6)$$

Where r is radius, a represent cross section of the coil, N represents the number of turns. The resistance of the winding is obtained by following formula;

$$R = \frac{\rho l}{A} \quad (7)$$

A, l, ρ represents area between two coils, length of the coil and resistivity of copper respectively. The length of the coil and circular area between two coils is given by following formula:

$$l = 2\pi DN \quad (8)$$

The resonant frequency is calculated by applying the following formula:

$$f = \frac{1}{2\pi\sqrt{DLC}} \quad (9)$$

Inductance reactance and capacitance reactance are obtained straight by the following formula;

$$X_L = 2\pi fL \quad (10)$$

$$X_c = \frac{1}{2\pi fC} \quad (11)$$

Energy oscillates at the resonant frequency between the inductor (energy stored in the magnetic field) and the capacitor (energy stored in the electric field) and is degenerates in the resistor. The quality factor for this resonator is;

$$Q = \frac{w_o L}{R} \quad (12)$$

The expression for Q shows the quality factor in the circuit. So, by reducing R, the quality factor of the system will increase.

IPT CIRCUIT DESIGN

The current flows in a primary coil are coupled with a resonant LC secondary coil. Current is induced in secondary coil at the transmission frequency, which frequency wants to set as a resonance frequency. The resonant frequency of the secondary coil can be calculated from the inductance and capacitance of the LC circuit. Figure-3 showed the circuit configuration for IPT. This circuit was designed by using NI Mutisim 14.0 software. This circuit consists of resistor, capacitor and transistor.

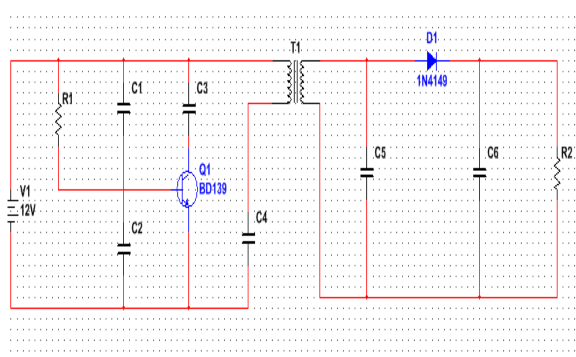

Figure-3. DC IPT circuit configuration.

The main function of a diode is to block the current in one direction, and allow current to flow in the other direction. Current flowing through the diode is called forward current. Table-1 showed the value of track and pick-up component in circuit simulation design.

Table-1. Track & pick-up component value.

Track & input inductance	TI Primary coil	20uH
Pick-up inductance	TI Secondary coil	50uH
Input Voltage	V1	6V
Primary capacitance	C1,C2,C3,C4	3.12uF
Pickup capacitance	C5	1.26uF
Output filter capacitance	C6	100nF

The IPT system has been developed in prototype as shown in Figure-4 to test the function of circuit designed. The circuit consist of track or transmitter and pick-up or receiver circuit. At the pick-up part, LED was used as a load.

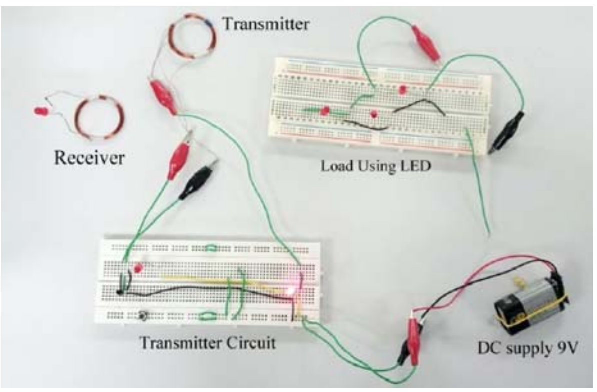

Figure-4. IPT hardware prototype part.

RESULT & DISCUSSION

The IPT system shown in Figure-3 was simulated using the NI Multisim software. The details of the simulated IPT system are given in Table-2.

Table-2. Simulation data of IPT system.

Input Voltage	6V
Voltage at Primary (Track)	4.96V
Voltage at Secondary (Pick-up)	769mV
Current at Primary	24.7mA
Current at Secondary	49.4mA
Frequency at Primary	24.6kHz
Frequency at Secondary	24.6kHz

The circuit simulation shows that the frequency at track and pick-up side is 24.6 kHz. Mean that both sides are at the resonance frequency. The resonant frequencies of the transmitting element and the receiving element are the most important parameters in wireless power transmission.

The track voltage also was reduced from 6V to 4.96Vdue to resistance and others component in the circuit. The output voltage at the pick-up is depending on the distance of both coils. As the distance increase, the value of output voltage will decrease. The value of output voltage reduces when the air gap between the track and pick-up part is increasing until the output voltage is zero (maximum length). Table-3 showed the value of voltage induces versus distance between the track & pick-up for hardware prototype measurement. The 6VDC was used as input voltage in the experiment.

Table-3. Voltage induce vs distance between coils.

Distance (cm)	Pick-up Inductance 20uH	Pick-up Inductance 50uH
0	3.5V	4.5V
1	3.11V	4.35V
2	2.82V	4.11V
3	2.56V	3.95V
4	2.23V	3.73V
5	1.95V	3.25V
6	1.73V	2.91V
7	1.51V	2.75V

Figure-5 shows that the voltage induced slightly decrease when the distance between two coils are increase. The maximum distance achieved in the experiment is 7cm with output voltage 1.51V for 20uH and 2.75 for 50uH.

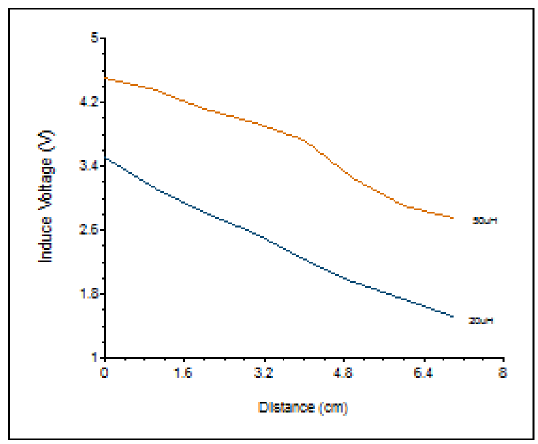

Figure-5. Induce voltage VS distance for 20uH & 5ouH.

Table-4 showed the measurement of current at the pick-up coils. LED was used as a load in the experiment. By using equation (5), the power can be determined as shown in Table-5.

Table-4. Distance vs current for 20uH & 50uH.

Distance (cm)	Current (A), 20uH	Current (A)50uH
0	0.035	0.062
1	0.030	0.055
2	0.024	0.049
3	0.019	0.043
4	0.013	0.038
5	0.009	0.032
6	0.005	0.026
7	0.001	0.022

Table-5. Power vs distance.

Distance (cm)	Power (W), 20uH	Power(W) ,50uH
0	0.1125	0.279
1	0.0933	0.239
2	0.0677	0.201
3	0.0486	0.170
4	0.0290	0.142
5	0.0176	0.104
6	0.0087	0.076
7	0.0015	0.061

The circuit was designed for low-power IPT application. The power can be increased by given more input voltage at the track and increase the value of inductance at the pick-up. By increasing the input voltage more flux will be generated and electromagnetics induction can be increased as derives in equation (1). The values of inductance at the pick-up also important because it will determine the radius and number of coils of the circuit as derived in equation (6).

CONCLUSIONS

A low-cost IPT circuit designed has been developed and tested. Both simulation and experimental result have been presented. The voltage induces, current and power at the pick-up side has been measured to prove that power can be transmitted via resonant coupled coils.

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