Magnetic Resonance Coupled Wireless Power Transfer with Class-E Power Amplifier from solar input

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Abstract

Wireless power transmission is the transmission of electrical energy from a power source to an electrical load, such as an electrical power grid or a consuming device, without the use of discrete human-made conductors. The principle of operation of wireless power transmission was established by Nikola Tesla in the early 1900's. In this project we use the renewable energy (solar power) as the source for wireless power transmission. The output from the renewable source is low, so it will be boosted using a high step-up DC-DC converter. This high voltage is then converted high frequency AC using class E Amplifier. The oscillating signals are then fed into the transmitter setup. By achieving proper resonance coupling between the transmitter and the receiver setup power gets transferred wirelessly. The transferred energy is converted back to DC using rectifiers and given to the DC load. The proposed model is a closed loop network with PI Controller. The proposed wireless power transmission system will be validated and verified using MATLAB/SIMULINK.

I. INTRODUCTION

Wireless power transmission is the transmission of electrical energy from a power source to an electrical load, such as an electrical power grid or a consuming device, without the use of discrete human-made conductors.The principle of operation of wireless power transmission was established by Nikola Tesla in the early 1900's. Nikola Tesla invented a resonant transformer known as Tesla coil, which was used to transfer power wirelessly using radiative method. The research team in MIT put forward mid-range wireless power transmission technology based on magnetic coupling resonance on the AIP forum in the United States, and experimentally demonstrated a 60W bulb being lit up over 2m distance in June 2007.

The wireless power transmission is achieved by three ways: Electromagnetic wave, Electromagnetic induction mode, Magnetic coupling mode. In magnetic coupling mode they are two types: Short range electromagnetic induction, mid-range strongly coupled magnetic resonance. Electromagnetic wave technology is used for long transmission distance with low efficiency. It also has greater impact on surrounding environment. Electromagnetic induction mode is a short transmission distance which is being limited to centimeters, even millimeters level. In magnetic coupling mode two matched resonant objects resonant in a certain frequency, there would be a strong coupling, thus the energy transfer would be more efficient.

A boost converter (step-up converter) is a power converter with an output DC voltage greater than its input DC voltage. It is a class of switching-mode power supply (SMPS) containing at least two semiconductor switches (a diode and a transistor) and at least one energy storage element. Filters made of capacitors (sometimes in combination with inductors) are normally added to the output of the converter to reduce output voltage ripple. Power can also come from DC sources such as batteries, solar panels, rectifiers and DC generators. A process that changes one DC voltage to a different DC voltage is called DC to DC conversion. A boost converter is a DC to DC converter with an output voltage greater than the source voltage. A boost converter is sometimes called a step-up converter since it "steps up" the source voltage. Since power ($P = VI$ or $P = UI$ in Europe) must be conserved, the output current is lower than the source current. A boost converter may also be referred to as a 'Joule thief'. This term is usually used only with very low power battery applications, and is aimed at the ability of a boost converter to 'steal' the remaining energy in a battery. This energy would otherwise be wasted since a normal load wouldn't be able to handle the battery's low voltage.

The main purpose of a power amplifier in this paper is to generating the alternating signals in the transmitter. But the power loss of these amplifiers is very high. So for achieving the greater efficiency by using class E amplifier for producing the AC signals for transmission. The oscillating signals are then fed into the transmitter setup. By achieving proper resonance coupling between the transmitter and the receiver setup power gets transferred wirelessly.

The output of receiver coil is AC. It is converted to DC using a AC to DC bridge rectifier. Capacitive filter is used to remove the ripples after rectification.

Fig 1 shows the block diagram of the Wireless Power Transmission System model. It consists of a solar panel which will be used as an input source, whose input voltage will be boosted using a high step-up DC-DC converter. This high voltage is then converted high frequency AC using class E power amplifiers. The oscillating signals are then fed into the transmitter setup. By achieving proper resonance coupling between the transmitter and the receiver setup power gets transferred wirelessly.

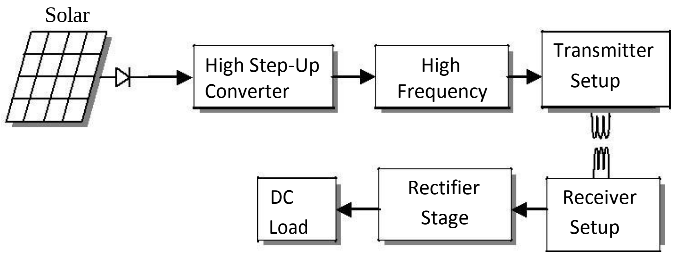

Fig 1, Block diagram of the proposed wireless power transmission system

II. DESCRIPTION OF THE PROPOSED WIRELESS POWER TRANSMISSION SYSTEM

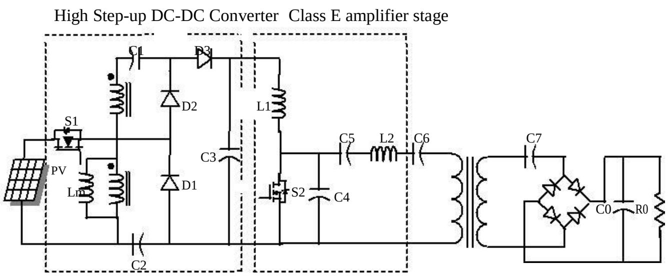

Fig 2, Circuit configuration of the proposed wireless power transmission system.

The fig 2 shows the two main stages of the proposed system. The first stage is the high step-up dc-dc converter which converts the low input voltage from the PV Cell to a higher value. The step-up converter has following advantages:

I. The converter has a high step-up conversion ratio because of the connection of the coupled inductors, diodes and the capacitors.

II. It has very high efficiency and lower stress on the switches as the leakage inductor energy can be recycled.

It consists of a coupled inductor T1 with the switch S1.The primary side winding N1 of a coupled inductor T1 is identical to the input inductor of the traditional boost converter, and diode D1, capacitor C1 receives leakage inductor energy from N1. The secondary side winding N2 of coupled inductor T1 is connected with another pair of diode D2 and capacitors C2, which are in series with N1 in order to increase the boost voltage. The rectifier diode D3 is connected to output capacitor C3.

The second stage is the class E amplifier which receives the dc input from the high step-up converter and converts to high frequency ac. The class E amplifier is a high efficient switch mode resonant converter. The high efficiency results from the reduced power losses in the transistor. The higher efficiency of the switch can be achieved by:

I. Using the transistor as a switch to reduce the power

II. Reducing the switching losses which result from
Finite transition time between ON and OFF states of the transistor.

The Class E amplifier consists of a RF choke L1 and a parallel-series resonator circuit consisting of C4, C5 and L2.

The output of the class E power amplifier is connected to the tank circuit formed by C6 and the transmitting coil as shown in the fig 2.

The receiver consists of a tank circuit formed by capacitor C7 and the receiving coil and a simple full bridge diode rectifier to convert the ac power transmitted from the transmitter coil to dc and a filter C0 is used to reduce the harmonics and then given to the load R0. The power gets transferred resonant frequency is achieved between transmitter and receiver pair.

III. MODES OF OPERATION OF THE PROPOSED WIRELESS POWER TRANSMISSION SYSTEM

There are five modes of operation for high step-up dc-dc converter and class E amplifier has only two modes which will be discussed separately.

A. Modes of Operation of High Step-Up DC-DC Converter:

Mode I (t0 – t1): Fig 3 shows the mode I operation of thestep-up converter. When the switch S1 is closed, the capacitor C2 gets completely charged by the magnetizing inductor Lm. The magnetizing inductor current ILm decreases as the input voltage Vin crosses the magnetizing inductor Lm and the leakage inductor Lk1. Lm still continues to transfer energy to the capacitor C2 but this energy is decreasing. The current through the diode D2 and the capacitor C2 are also decreasing. The secondary leakage current iLk2 is also decreasing with a slope of iLm/n. This mode ends when increasing iLk1 is equal to the decreasing iLm at t=t1.

Mode II (t1 – t2): Fig 4 shows the mode II operation of thestep-up converter. During this mode, the input source voltage Vin gets series connected with N2, C1 and C2 which charge the Output capacitor C3. The currents iLm, iLk1 and id3 increases as Vin crosses Lk1, Lm and N1. Lm and Lk1 stores energy from Vin

Also C1 and C2 discharge their energy toC3. Hence id3 and the discharging currents ic1 and ic2 also increase. The switch is turned off at t=t2 and this mode ends.

Mode III (t2 – t3): Fig 5 shows the mode III operation ofthe step-up converter. During this mode the secondary leakage inductor Lk2 keeps charging the output capacitor C3 when the switch is turned off at t=t2. Diodes D1 and D 3 will be conducting. The stored energy in Lk1 flows through D1 to charge the capacitor C1. Also, the stored energy in the leakage inductor Lk2 is in series with C2 to charge the output capacitor C3. Since the inductances of Lk1 and Lk2 are very small
Compared to Lm, iLk2 decreases rapidly but iLm increases as the magnetizing inductor Lm receives energy from Lk1. This mode ends when iLk2 decreases and reaches zero at t = t3.

Mode IV (t3 – t4): Fig 6 shows the mode IV operation ofthe step-up converter. The magnetizing inductor Lm discharges its energy to C1 and C2. Diodes D1 and D2 are conducting in this mode. The currents i0 and i D1 are decreases continuously as the leakage energy charge the capacitor C1 through the diode D1. The magnetizing inductor Lm discharges its energy to charge the capacitor C2 through T1 and D2. The energy stored in C3 is continuously discharged to the load R. These energy transfers decreases the currents iLk1 and iLm but increases the current iLk2.This mode ends when iLk1 reaches zero at t=t4

Mode V (t4 – t5): Fig 7 shows the mode V operation of thestep-up converter. During this mode of operation, Lm continuously discharges its energy to C2 and diode D2 will be conducting. The current iLm decreases as it charges the capacitor C2 through T1 and D2. This mode ends when the switch S1 is turned on at the beginning of the next switching period.

B. Modes of Operation of Class E Power Amplifier:

Fig 8 shows the two switching stages of the switch S1 which is ON for a half cycle and off for another half cycle. The switch S1 is turned ON at zero drain voltage and zero drain current to reduce the switching losses when the transistor is turned ON.

Optimum Operation Mode: When the switch is turnedOFF, there will be a jump change in the drain current but the drain voltage starts to increase slowly from zero thus reducing the switching losses. This will be the optimum mode of operation of class E amplifier as ZVS and ZCS has been achieved which provides the highest efficiency.

Sub-Optimum Operation Mode: Class E amplifier can beoperated in a sub-optimum operation mode, where the capacitor C1connected across the switch S1 is discharged to zero before turning ON the switch S1 by proper gate signals. In this case the drain voltage becomes negative and the anti-parallel diode of the switch S1 conducts only the negative current and maintains the drain voltage close to zero before the switch S1 is turned ON, thus reducing the switching losses.

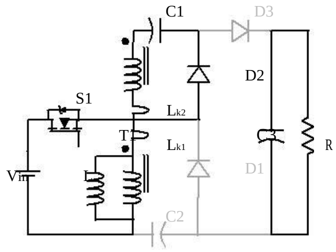

Figure 3, Mode I operation of high step-up dc-dc converter

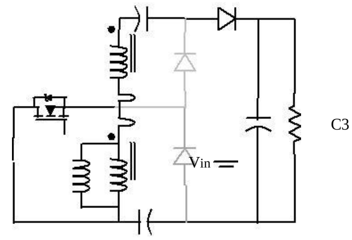

Figure 4, Mode II operation of high step-up dc-dc converter

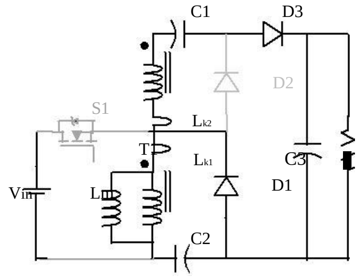

Figure 5, Mode III operation of high step-up dc-dc converter

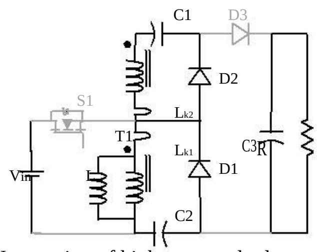

Figure 6, Mode IV operation of high step-up dc-dc converter

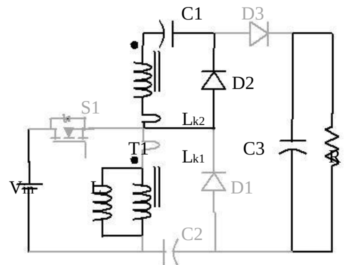

Figure 7, Mode V operation of high step up dc dc converter

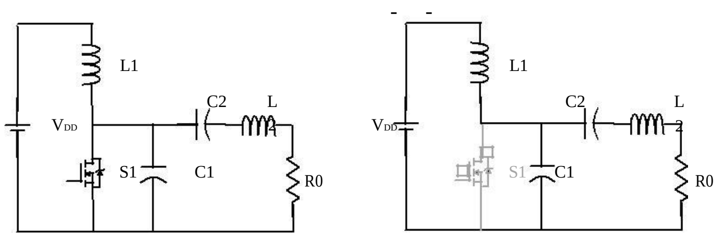

Figure 8, Operation of Class E Power Amplifier

IV. DESIGN OF THE PROPOSED WIRELESS POWER TRANSMISSION SYSTEM

The design of the proposed WPT system requires the design of the high step-up dc-dc converter and the design of the class E power amplifier. Hence, there are two design stages which will be discussed in this section. During the design procedure, following assumptions are made:

I. All the components are assumed to be ideal

II. The ON state resistance and the parasitic capacitance of the switches are neglected.

III. The voltage drops across the diodes are neglected.

IV. The capacitors are assumed to have a very large value.

A. High Step-Up DC-DC Converter Design:

Input Voltage V_{in} = 12 V (1)
Output Voltage V_0 = 70 V (2)
Switching frequency f = 100 KHz (3)
Transformer turns ratio n = 2 (4)
Output R = 100 Ω (5)

Now the duty cycle D is calculated as

$$D = 1 - \frac{Vin\,(1+n)}{v} \quad (6)$$

$$D = 1 - \frac{12(1+2)}{70}$$

D = 0.485 or 48.5% (7)

The boundary normalized magnetizing time constant τ_{LB} is
depicted as,

$$\tau_{LB} = \frac{D(1-D)^2}{(1+n)^2} \quad (8)$$

At the boundary for converter's operation at 50% of the full load, the load resistance R=200Ω is selected. Substituting the value of D in the equation 4.8, we have

$$T_{LB} = \frac{0.485(1-0.485)^2}{2(1+2)^2}$$

$$T_{LB} = 7.1371 \times 10^{-3}\ \text{s} \quad (9)$$

Now the boundary magnetizing inductance is found as,

$$L_{mB} = \frac{T_{LB}\,R}{f} = \frac{7.1371 \times 10^{-3} \times 100}{50\times10^3}$$

$$L_{mB} = 14.275\ \mu\text{H} \quad (10)$$

Hence the magnetizing inductance L_m has to be greater than the boundary magnetizing inductance L_{mB} i.e., $L_m > 14.275\ \mu$H (11)

B. Class E Transmitter Design:

To start with we have to first set the supply voltage of the class E power amplifier by using the equation.

$$VCC = \frac{BV_{CEV}}{3.56}.SF \quad (12)$$

Where BV_{CEV} is the breakdown voltage of the MOSFET which is to be used and SF is the safety factor whose value is not greater than 1. Assuming SF to be 0.8 and the supply voltage of 70 V, we have

$$BVCEV = \frac{3.56\times V_{CC}}{SF} \quad (13)$$

$$= \frac{3.56\times70}{0.8} = 311.5$$

i.e. we have to choose a MOSFET whose breakdown voltage has to be greater than 311.5V.

Based on the power specification and QL, the load resistance can be calculated based on the following equation as shown in 14.

$$RL = \frac{(V_{cc})^2}{POut} 0.576801 \left(1.001245 - \frac{0.451759}{Q_L} - \frac{0.402444}{Q_L^2}\right.$$

Error! Bookmark not defined.) (14)

Where the value of QL is chosen by the designer, for a duty cycle of 50%, the minimum value of QL is 1.7879. In [8] the value of QL is chosen to be 2.134 and POut as 60 W, we have

$$R_L = \frac{(70)^2}{60} 0.576801 \left(1.001245 - \frac{0.451759}{2.134} - \frac{0.402444}{2.134^2}\right)$$

R_L= 32.98 Ω

Hence the value of RL is chosen to be R_L = 50 Ω

The next step is to calculate the value of the shunt capacitance C_1 which is to be connected across the switch bythe following equation.

$$C_1 = \frac{1}{2\pi f_0 R_L (\frac{\pi^2}{4}+1)\frac{\pi}{2}} \left(0.99866 + \frac{0.91424}{Q_L} - \frac{1.03175}{Q_L^2}\right) + \frac{0.6}{(2\pi f_0)^2 L_1} \quad (15)$$

$$C_1 = \frac{1}{34.2219 f_0 R_L} \left(0.99866 + \frac{0.91424}{Q_L} - \frac{1.03175}{Q_L^2}\right) + \frac{0.6}{(2\pi f_0)^2 L_1} \quad (16)$$

We have chosen the operating frequency of 13.56 MHz, substituting the value of $f_0$and R_L in the equation 16, we
have the value of shunt capacitance C_1 as

$$C_1 = 51.74\text{pF} + \frac{0.6}{(2\pi f_0)^2 L_1} \quad (17)$$

Usually the value of X_{L1} is chosen to be 30 or more than timesthe unadjusted value of X_{C1}.

i.e. $X_{L1} > 30 \times X_{C1}$ (18)

$\omega_{L1} > \frac{30}{\omega C_1}$

$L_1 > \frac{30}{\omega^2 C_1}$

Substituting the value of C_1 as 51.74pF and f_0= 13.56MHz, we have

$L_1 > 79.87\mu H$

The value of L_1 is chosen to be 80µH. Substituting this valueof L_1 in equation 17, the value of shunt capacitance C_1 is found to be

$C_1 = 79.4$ pF

The value of C_2 is calculated by using the equation below

$$C_2 = \frac{1}{2\pi f_0 R_L}\left(\frac{1}{Q_L - 0.104823}\right)\left(1.00121 + \frac{1.01468}{Q_L - 1.7879}\right) - \frac{0.2}{(2\pi f_0)^2 L_1} \quad (19)$$

Substituting the value of f_0, R_L and Q_L in the equation 19, we have

$C_2 = 689.9127$pF

The value of L_2 is found from the equation below

$$L_2 = Q_L \frac{R_L}{2\pi f_0} \quad (20)$$

Substituting the value of f_0, R_L and Q_L in the equation 20, we have

$L_2 = 0.8\mu H$

V. SIMULATION AND RESULTS

The simulation of the proposed wireless power transmission model has been carried out using MATLAB/SIMULINK. The proposed model has been verified for an input voltage of 12V from the solar panel and the output is obtained to be 110V.

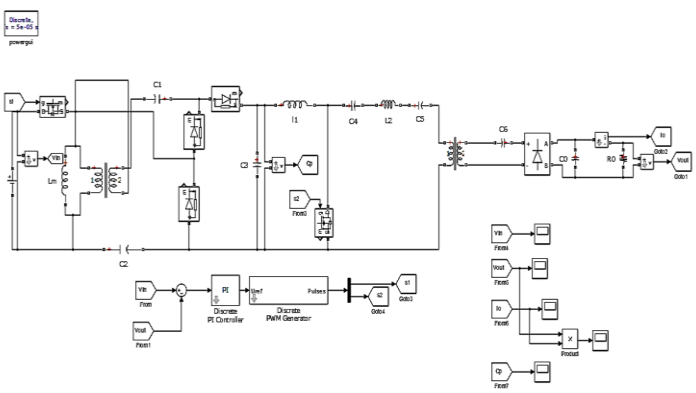

Figure 9, Circuit arrangement of the proposed wireless power transmission system using MATLAB/SIMULINK package.

The specifications of various components used in the proposed model are tabulated below.

Sl no.	Parameter	Value
1	Lm	15µH
2	C1	47µF
3	C2	47µF
4	C3	470µF
5	Duty ratio of S1	48.5%
6	Turns ratio of T1	2
7	L1	80µH
1	L2	0.8µH
2	C4	690pF
3	C5	132pF
4	C6	150pF
5	C0	68uF
6	R0	400Ω
7	Duty ratio of S2	50%

Figure 10, Component values of the proposed Wireless Power Transmission model

The simulation of the proposed system has been verified using SIMULINK package. With an input of 12V from the solar panel, the high step-up converter boosts this voltage to 70V which is shown in fig 11. The output of the high step-up converter is measured across the capacitor Cp.it has the improved rise time of 50% (i.e 0.05)[1].

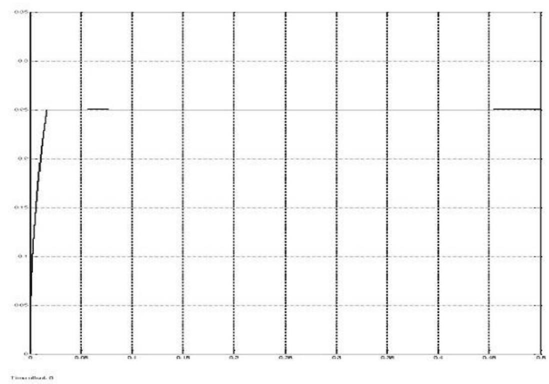

Figure 11, Output across the capacitor Cp

The output voltage of the dc-dc converter stage is represented along the Y-axis in volts and time in X-axis and is measured to be 70V.

The second stage consists of a wireless power transmission setup using class E transmitter. An input of 70V is applied to the second stage and an output of 110V DC is to be obtained. The Fig 12 represents the output voltage at the secondary side of the proposed wireless power transmission model.

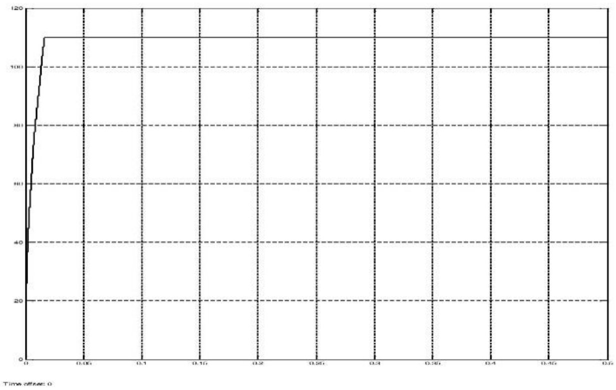

Figure 12, Output voltage of the proposed system

The fig 12 is the plot of output voltage versus time with voltage on the Y-axis in volts and time along X-axis in seconds.It is observed that the output voltage at the secondary of the wireless power transmission model is found to be 110V. It has the improved raise time of 50%(i.e 0.05)[1].

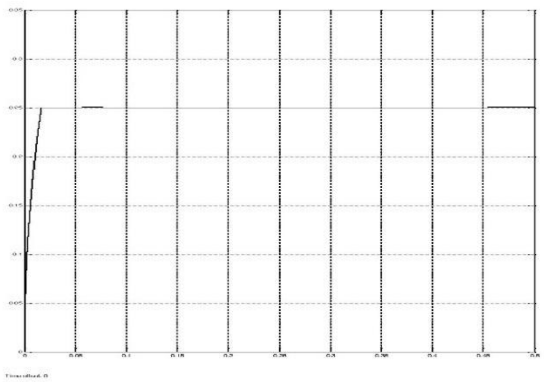

Figure 13, Output current of the proposed system

The Fig 13 represents the output current flowing through the secondary side of the proposed wireless power transmission model. The output current is represented along Y-axis in amperes and time along X-axis in seconds. It is observed that the output current flowing through the proposed wireless power transmission model is found to be 250mA. *I*t has the improved rise time of 50% (i.e 0.05)[1].

The output power which is a product of voltage and current is found to be 27V theoretically and is found to be 27.5 from the simulation. The fig 14 shows the output power off the proposed wireless power transmission system. it has the improved rise time of 50% (i.e 0.05)[1].

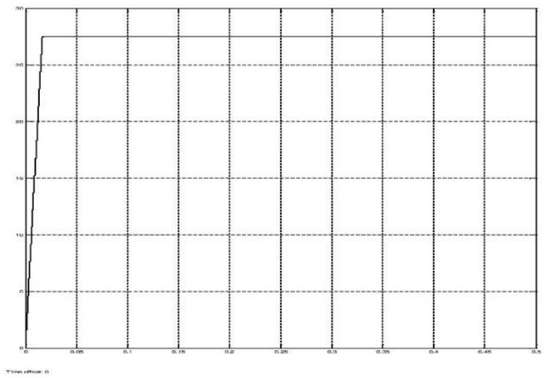

Figure 14, Output power of the proposed system

The fig 14 is a plot of output power P0 long Y-axis and time along X-axis.

CONCLUSION

This project has introduced the transmission of power wirelessly using the input from the solar panel. The proposed wireless power transmission using high step-up dc-dc converter for PV cells has been built based on the simulation performed on MATLAB/ SIMULINK. The model uses the input from the solar panel and by using a high step-up dc-dc converter, the input of 12V hasbeen stepped up to 70V which is the given as the input to the class E transmitter. The secondary or the receiver of the proposed model receives a DC output of 110V and the power delivered to the load is nearly28W. And also we improved the raise time by using a closed loop PI Controller network(i.e 50%)[1].

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