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Design Of a Prototype Wireless Power Transmission System for A 50W Load

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Abstract: The proposed paper discusses on the possibilities of transmitting power wirelessly over certain small distances for a load of 50W (maximum 75W). The system consists of mainly five blocks namely: AC-DC rectifier, DC-AC high frequency inverter, resonating circuits, DC-AC high frequency rectifier and a closed loop buck converter. This particular system is designed to operate in the radio frequency bandwidth of 25kHz to 150kHz. The system is designed keeping in mind applications such as very low power electric cycle and laptop chargers. This concept can be extended for mid-range WPT systems mainly wireless EV charging by changing few devices.

***Index Terms* - WPT, PTC, DC-AC High Frequency Inverter, Buck Converter, Wireless EV Charging.**

I. Introduction

The technology for wireless power transmission or wireless power transfer (WPT) is in the forefront of electronic development. The main function of wireless power transfer is to allow electrical devices to be continuously charged and overcome with the constraint of a power cord. In day-to-day life many applications are witnessed which are powered using tangled wires. The concept of wireless power transmission has been there since 1886. Hertz performed experiment with pulsed wireless energy transfer, he produced an apparatus that produced and detected microwaves in UHF (ultra-high frequency) region. Tesla also performed experiment in the field of wireless energy transfer in 1899.

WPT system is a very necessary field of research as this technology can be extended to many devices in day-to-day life to make life comfortable. To understand in a better way let us consider two coils namely transmitting coil Tx and receiving coil Rx which send and receive power on the principle of mutual inductance. As stated by Faraday when current passes through a conductor magnetic field is created which surrounds the conductor. Similarly, the varying current during the transmission time produces time varying magnetic field. When this magnetic field cuts another conductor, an EMF is induced into the conductor. This phenomenon is known as Faraday's Law of Electromagnetic Induction.

In a wireless power transmission system, a transmitter device driven by electric power from a power source generates a time varying EM (electromagnetic field) which transmits power across space to a receiver device which in turn converts the electrical energy into desired form. Wireless power transmission mainly falls into two categories namely near field and far field. This paper focuses on near field or non-radioactive power transfer technique using inductive coupling between coils of wire at a frequency of 130kHz

II. LITERATURE SURVEY

2.0 EXISTING SYSTEM

The existing WPT systems are used to charge mobile phones whose voltage rating is very small and total power output is also, less. The extension of WPT for mid and high range power is still under research. This manuscript will help and explain in designing a WPT system for a load of 25V, 50W (Maximum 75W).

2.1 PROPOSED SYSTEM

This paper is an attempt to design a WPT system which is powered using 230V, 50Hz single phase AC. This system can be used to power a maximum load of 50W keeping the frequency fixed at 130kHz (which can be varied from 25kHz to 150kHz).

This system comprises mainly of five blocks as seen in Fig 1.0. The first block is the rectifier block which converts the input single phase AC voltage to DC. The second block is a high frequency inverter which converts our DC to high frequency stepped AC, which is significant to achieve wireless transmission. The third block comprises of resonating circuits and their corresponding transmission and receiving coils. The fourth block is a high frequency rectifier circuit which converts high frequency AC to DC. The last block is the closed loop buck converter which converts DC voltage to lower value of DC voltage.

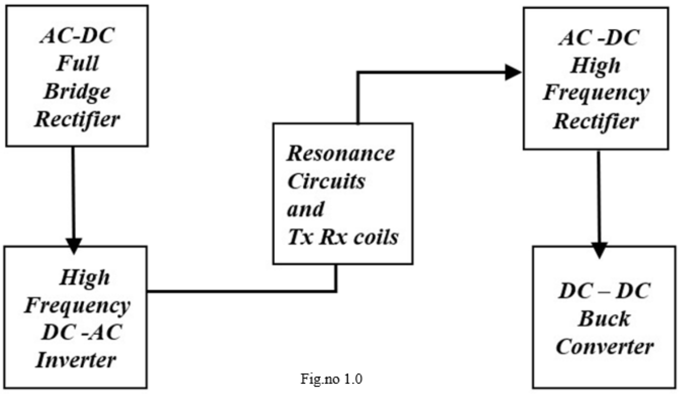


Fig.no 1.0

III. Power Converter Blocks

3.0 AC-DC Full Bridge Rectifier:

Generally, a WPT system works at high frequencies hence, there is a need to increase the frequency of the AC input. To do so, first convert 230V 50Hz single phase AC into DC voltage. The above conversion can be achieved using a full bridge rectifier. As shown in the fig 1.1, 50Hz AC voltage enters the circuit and gets rectified to pulsating DC voltage with the help of the diode bridge. The capacitor followed by the bridge is used to hold the voltage and to reduce the ripple
i.e., the AC component present in the rectified pulsating DC voltage. A value of 450V, 470uF is chosen for optimal functioning of the rectifier. Instead of the four diodes configuration for the full bridge rectifier, it is replaced with a single unit which can handle a current of 25A and a voltage of 800V. The pin diagram in shown in fig 1.1.

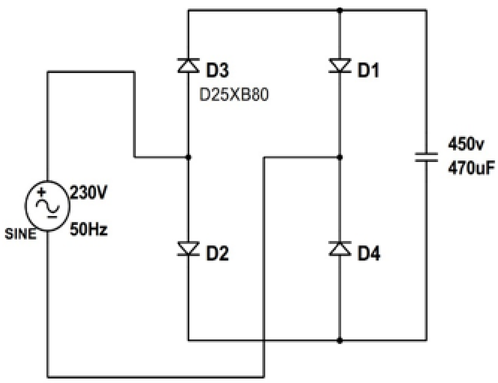


Fig.no 1.1

Assembled circuit also contains a PTC of 4.5ohms connected in series with input supply, which was selected on experimental basis. It is for the slow rise of current during the capacitor charging state as, capacitor without a PTC draws huge amount of current during turn on. Thus, by adding a PTC we can avoid damage to any of the components.

3.1 DC-AC High Frequency Inverter:

For any WPT system to transfer wireless power, the fundamental idea is to transmit the power in radio wave frequency range. So, the rectified DC voltage is converted to high frequency AC voltage using a full bridge inverter as shown in fig 1.2. The inverter switching is controlled using the gate drive IC's IR2104. Each gate drive IC's can turn on two MOSFET's or a single leg together.

When an input DC voltage is provided to the inverter, the gate drive ICs at that moment switch at the desired frequency, i.e., 130kHz. The DC voltage simultaneously keeps switching at a frequency of 130kHz from negative peak to positive peak. This voltage is fed to a LC resonating circuit which comprises of capacitor and flat spiral coil, which together forms the transmission system.

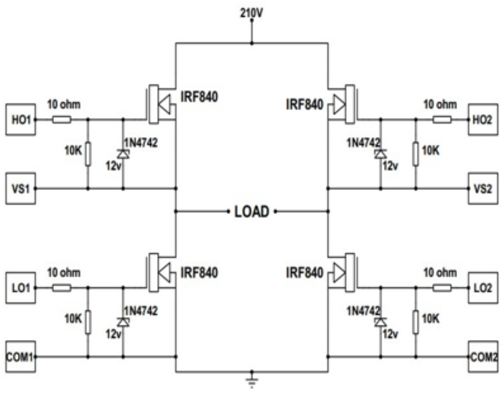


Fig.no 1.2

3.2 AC-DC High Frequency Rectifier:

This block is fed with high frequency AC voltage received from the secondary coil. The circuit comprises of a full bridge rectifier similar to one used in the first block but, is designed for high frequency AC voltage. The diodes used for this application must be operational at high frequencies and reverse recovery of these diodes must be very fast. For this reason, SCS220AG is used as shown in fig 1.3.

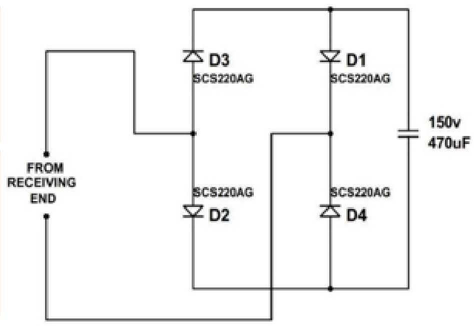


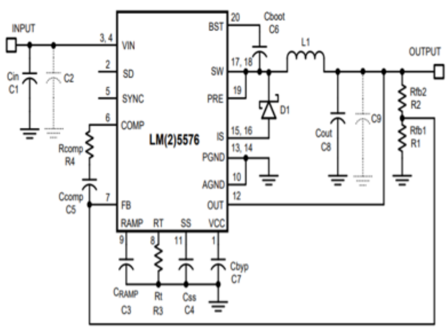
Fig.no 1.3

The rectified DC voltage is now available across the output terminals of the bridge rectifier. The DC voltage available after rectification is a pulsating DC. To filter the AC component out of the pulsating DC an electrolytic capacitor of 150V and 470uF is used. This capacitor holds the peak value of the pulsating DC voltage. The capacitance value of the capacitor is chosen by assuming ripple to be 40% and for an efficiency of 81%.

3.3 DC-DC Buck Converter:

The main application of these WPT systems is mobile, Laptop chargers, wireless charging of electric vehicles etc. The common thing among all these circuits is that the final voltage for these devices to charge is a DC voltage as all these devices are battery powered. For this reason, it is important to convert the received DC voltage to a lower value. DC voltage can be lowered using various converter circuits like buck, flyback, resonant converter etc.

But, considering the simplicity of design of the buck converter, the Texas Instrument IC LM5576 is used. The Texas instruments IC LM5576[1] is a 20pin TSSOP package buck regulator, which can handle input voltage ranging from 6V to 75V. The voltage output of this IC can vary from 1.25V to 70V. But for the proposed application the output of this IC should be limited to 25V. The IC can also deliver a maximum current of 3A. The pin configurations are given in fig 1.4



Credit: Texas Instruments [1]

Fig.no 1.4

The other advantage of this IC is that no separate power supply is required to power the IC, as the IC internally generates the required voltage to turn on from the input voltage. The application note [1] of IC LM5576 can be referred for customizing the circuit design as per particular requirements.

VI. ADDITIONAL CIRCUITRY

4.0 Auxiliary Power Supply:

The need for a secondary power supply is for powering low voltage IC's such as the gate drive IC SG3525N, the PWM generator IC IR2104 and the shutdown pin of the ICSG3525. The auxiliary power supply is a full bridge rectifier whose input is given from a 230V/18V stepdown transformer.

The rectifier converts the stepdown AC voltage to the corresponding DC voltage. This is followed by two regulator IC's namely 7812 and 7805 whose function is to regulate the voltage to 12V and 5V. The purpose of the capacitors shown in fig 2.0 is to eliminate the AC ripple present in the rectified DC voltage. The arrangement of the capacitors in the circuit can be inferred from their corresponding application notes

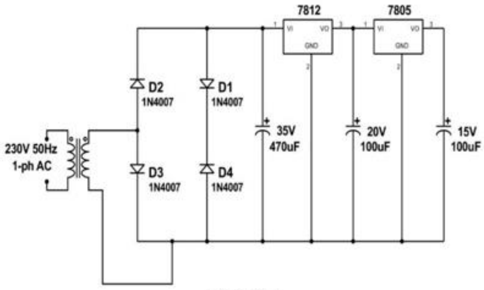


Fig.no 2.0

There are many alternative circuits for a secondary power supply. The most common among these circuits is the flyback converter. Flyback converter can be used for the above application but only disadvantage is that it would add on additional cost as, linear power supplies are comparatively less expensive to design rather than a SMPS power supply

4.1 Gate Drive Circuit for High Frequency Inverter:

This circuit is the heart of the high frequency inverter. It comprises of mainly two IC's which are SG3525N and IR2104. SG3525N is the IC responsible for the generation of PWM pulses which switch the corresponding MOSFET's with the help of gate drive IC IR2104.

The application notes of SG3525N [2] consists of the corresponding circuitry which will enable to generate the PWM signals. Similarly, the application notes of IR2104[3] consists of the corresponding circuitry shown in the fig 2.1.

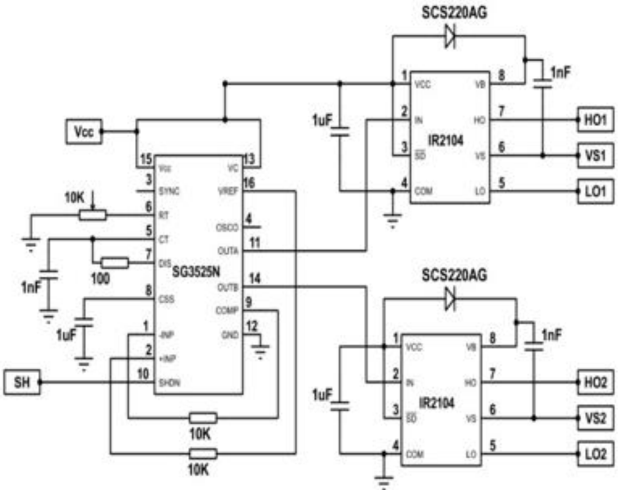


Fig.no 2.1

The diode used in the bootstrap circuitry must be a diode which operates at high frequency. Hence, SCS220AG a two-pin diode package is chosen. As seen in the fig 2.1, bootstrap circuit [4] is implemented to supply PWM pulse to the high side MOSFET. The frequency of the pulse generated by IC SG3525N can be varied from 25kHz to 150kHz with the help of the 10kohm potentiometer which is connected to the RT pin of the PWM generator IC

4.2 Shutdown Pin Circuit for IC SG3525N:

The shutdown pin in SG3525N is to control both output stages and soft start of the circuit. This helps in the soft start of MOSFET's during power on. The SD pin takes an active low input to remain in shutdown state and takes an active high input to start the PWM pulse generation. This simple application can be achieved using a low voltage transistor-based circuit.

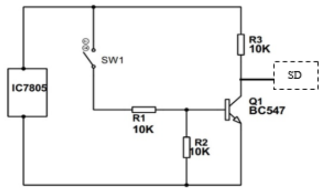


Fig.no 2.2

As seen in the fig 2.2, the switch SW1 when switched to turn on position, the SG3525 IC is not in shut down mode. Hence, outputs are available at the corresponding pins and vice versa when SW1 is turned off. This ensures that the MOSFET's are protected during the device turn on state.

4.3.0 WPT Resonance Circuit:

The basic principle of wireless power transmission is Faraday's law of electromagnetic Induction. For simplicity of understanding, consider a dual coil system as shown in fig 2.3 consisting of primary coil of single turn and a secondary coil of one turn.

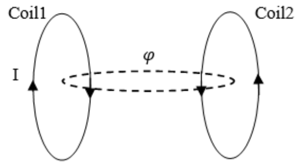


Fig.no 2.3

When voltage is applied across the primary coil, according to ohms law current starts flowing through the coil as the coil offers resistance. Faraday found that when current flows through a conductor, magnetic flux is generated. The magnetic fields direction can be determined using the right-hand thumb rule. When varying current flows through the primary coil, a varying magnetic flux is generated. And when this varying magnetic flux cuts the secondary coil, an EMF is induced. This phenomenon is the base for wireless power transfer.

$$\varepsilon = -N\frac{d\varphi}{dt}$$

where,
ε: Induced voltage
N: No of turns
dφ: Time varying magnetic flux
dt: Change in time

4.3.1 Types of WPT systems

The WPT systems are mainly divided into two categories inductive and capacitive power transfer. This paper discusses about inductive power transfer.

In inductive coupling (electromagnetic Induction or inductive power transfer, IPT), power is transferred between coils of wire by a magnetic field. The transmitter and receiver coils together form a transformer. An alternating current (AC) through the transmitter coil (Tx) creates an oscillating magnetic field (B) by Ampere's law. The magnetic field passes through the receiving coil (Rx), where it induces an alternating EMF (voltage) by Faraday's law of induction, which creates an AC current in the receiver. The induced alternating current may either drive the load directly or be rectified to direct current (DC) by a rectifier in the receiver, which drives the load. A few systems such as electric toothbrush charging stands, work at 50 Hz so AC mains current is applied directly to the transmitter coil but, in most systems an electronic oscillator generates a higher frequency current which drives the coil because transmission efficiency improves with frequency.

Why resonance circuit? When resonance occurs, the current caused by the collapsing magnetic field in the inductor charges the capacitor. The discharging capacitor then drives a current through the inductor that produces a magnetic field. The energy in the system shifts between magnetic energy and electric energy. In the ideal case there are no loss and the system will continue to resonate. During this condition the effective impedance is zero as the inductive reactance will be equal to capacitive reactance. Hence, maximum power can be transmitted. So, the systems are tend to be operated at resonance.

A simple series LC resonating circuit is considered. Depending on the frequency of operation desired value of capacitance is assumed and inductance is calculated

4.4 Rx and Tx Coil Design and Calculations:

There are many different kinds of materials that can be used to wind these coils. The material used here will be the Litz wire. Litz[4] wire is a particular type of multistrand wire or cable used in electronics to carry alternating current (AC) at radio frequencies. The wire is designed to reduce the skin effect and proximity effect losses in conductors used at frequencies up to about 1 MHz . It consists of many thin wire strands, individually insulated and twisted or woven together, following one of several carefully prescribed patterns often involving several levels (groups of twisted wires are twisted together, etc.). The result of these winding patterns is to equalize the proportion of the overall length over which each strand is at the outside of the conductor. This has the effect of distributing the current equally among the wire strands, reducing the resistance. Litz wire is used in high Q inductors for radio transmitters and receivers operating at low frequencies, induction heating equipment and switching power supplies. The Coil will be wound in the flat tesla coil shape as shown in fig 2.4 to increase the magnetic flux linkage between the two coils. Also, a ferrite core will be placed under these two coils to increase the coupling coefficient between these two coils.

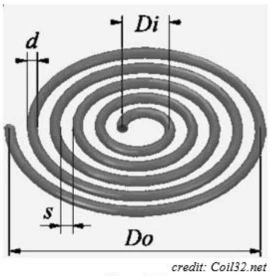


Fig.no 2.4

L: Required inductance
Di: Coil inner diameter
d: Wire thickness
s: Gap between Turns
The calculations for number of turns can be found using JC Maxwell software [5] or coil32.Net [6] flat spiral tesla coil design software. Once the Tx is designed Rx turns can be found in the following way.
We know for a transformer

$$\frac{V2}{V1} = \frac{N2}{N1}$$

V1: Primary Voltage
V2: Secondary Voltage
N1: Primary no of turns
N2: Secondary no of turns
Similarly, the above equation can be modified for air core system

$$\frac{V2}{V1} = k\,\frac{N2}{N1}$$

Here
k: coupling coefficient.

V. Equations

5.0 Mathematical Equations for Rectifier:
Vin: Input RMS AC voltage
Vm: Maximum input AC voltage

$$Vm = \sqrt{2}\,Vin \qquad ---(1)$$

Vavg: Average Output DC Voltage
Voutm: Maximum Output DC Voltage

$$Vavg = 2Vm/\pi \qquad ---(2)$$

η: Efficiency (Designed for an efficiency of 81.2%)
r: Ripple (0.48 for a efficiency of 81.2%)
f: Frequency of ripple voltage
C: Capacitance
R: Load resistance
Pout: Power output

$$r = 1/\,(4\sqrt{3}\,fCR) \qquad ---(3)$$

$$R = Voutm\,/\,Pout \qquad ---(4)$$

5.1 Mathematical Equations for Inverter:
Vo: Output voltage of inverter
Vin: Input voltage of inverter
∂: Pulse width of the inverter output voltage

$$Vo = \sum_0^\infty Vo1,n\ \cos(n\omega t) + \sum_0^\infty Vo2,n\ \sin(n\omega t) \qquad --[5]$$

$$Vo1,n = \frac{2}{\pi}\int_0^\pi Vin\sin(n\omega t)d(\omega t) \qquad --[6]$$

$$Vo2,n = \frac{2}{\pi}\int_0^\pi Vin\cos(n\omega t)d(\omega t) \qquad --[7]$$

$$Vo = Vin\sqrt{\frac{\partial}{\pi}} \qquad --[8]$$

5.2 Mathematical Equations for High Frequency Rectifier:

Vin: Input RMS AC voltage
Vm: Maximum input AC voltage

$$Vm = \sqrt{2}\ Vin \qquad \text{---(9)}$$

Vavg: Average Output DC Voltage
Voutm: Maximum Output DC Voltage

$$Vavg = 2Vm/\pi \qquad \text{---(10)}$$

η: Efficiency of the design
r: Ripple factor
f: Frequency of ripple voltage
C: Capacitance
R: Load resistance
Pout: Power output

$$r = 1/\ (4\sqrt{3}\ fCR) \qquad \text{---(11)}$$

$$R = Voutm\ /\ Pout \qquad \text{---(12)}$$

5.3 Mathematical equations for Buck Converter:

**Credits Texas Instruments [1]*

Fsw(max): Maximum Switching Frequency
Vin(mn): Minimum Input Voltage
Vin(mx): Maximum Input Voltage
Vout: Output Voltage

$$Fsw(max) = \frac{Vin(min) - (Vout + 0.6)}{(Vin(min) * 5.5 * 10\text{^}{-7}} \qquad \text{--(13)}$$

$$Rt = \frac{1/(Fsw\ )\ - 580 \times 10{-9}}{135 \times 10\text{^}{-12}} \qquad \text{--(14)}$$

$$L1 = \frac{Vout[1] \times (Vin(max)[3] - Vout[1])}{0.8 * Fsw * Vin(mx)} \qquad \text{--(15)}$$

$$Cramp = L1 * 10\text{^}{-5} \qquad \text{--(16)}$$

Rfb2 to 5kOhms if Vout is less than or equal to 5 Volts. If Vout is greater than 5V set Rfb2to 10kohm

$$Rfb1 = \frac{1.225 * Rfb2}{(Vout - 1.225)} \qquad \text{--(17)}$$

$$Cin = 1.5\ /Fsw \qquad \text{--(18)}$$

$$Rcomp = 6 * 104 * Rfb1 * Cout + (Rfb1/Vout) \qquad \text{--(19)}$$

$$Ccomp = 1/\ (8 * 103 * Rcomp) \qquad \text{--(20)}$$

5.4 Mathematical Equations for secondary power supply:

Vin: Input RMS AC voltage
Vm: Maximum input AC voltage

$$Vm = \sqrt{2}\ Vin \qquad \text{---(21)}$$

Vavg: Average Output DC Voltage
Voutm: Maximum Output DC Voltage

$$Vavg = 2Vm/\pi \qquad \text{---(22)}$$

η: Efficiency (Designed for an efficiency of 81.2%)
r: Ripple (0.48 for a efficiency of 81.2%)
f: Frequency of ripple voltage

C: Capacitance
R: Load resistance
Pout: Power output

$r = 1/(4\sqrt{3}\, fCR)$ ---(23)

R = Voutm / Pout ---(24)

5.6 Mathematical Equations Shutdown Pin Circuit:

Vin: Input DC voltage
Vbe: Base Emitter voltage
Rb: Resistor at Base terminal
Rc: Resistor at collector terminal
Ib: Base Current
Ic: Collector Current
β: Current Gain

Ib = Ic / β ---(32)

Rb = (Vin – Vbe) / Ib ---(33)

Rc = Vin / Ic ---(34)

5.7 Mathematical Equations Resonance Circuit:

f: Operating frequency
C: capacitance of resonance circuit (needs to be assumed)
L: Inductance of the coil
For Series resonance circuit

$$f = \frac{1}{2\pi\sqrt{LC}}$$ --(35)

VI. RESULTS AND DISCUSSION

The results for corresponding blocks are obtained experimentally for the given input condition Vin = 230V 50Hz 1 phase AC and Vout(Required) = 25V DC

6.1 AC-DC Rectifier:

Vin: 230V 50Hz AC
Vout: 337V DC (Fig 5.0)
ΔV (Ripple voltage): 340mV (Fig 5. 1)

6.2 DC-AC High Frequency Inverter:

Vin: 337V DC
Vout(pp): 432V AC (Fig 5.2 for more information)
Gate Drive IC output:
Vho1: 10.4V (Fig 5.3)
Vlo1: 10.3V (Fig 5.4)
f (Switching Frequency): 130kHz

6.3 AC-DC High Frequency rectifier:

(Simulation data, soon to replace with experimental data)
Vin(pp): 102V
Vout: 50V DC (Fig 5.5)
ΔV (Ripple voltage): 5V (Fig 5.6)

6.4 DC-AC Buck Converter:

(Simulation data, soon to replace with experimental data)
Vin: 50V DC
Vout: 24.6V DC (Fig 5.7)

6.5 Transmitting and Receiving results:

Vtx(pp): 203V (fig 5.8)

Vrx(pp): 102V (fig 5.9)

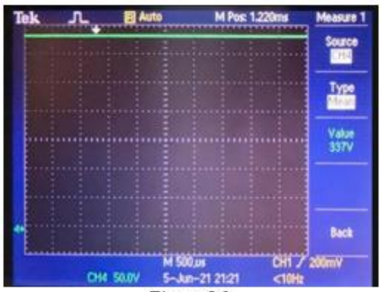


Fig.no 5.0

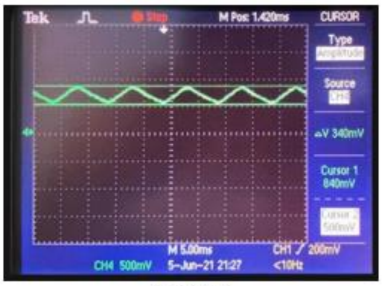
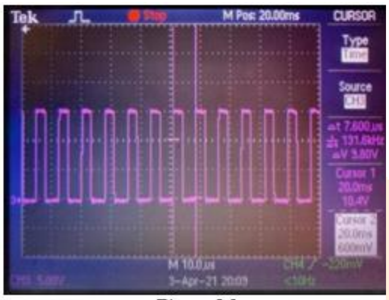


Fig.no 5.1

Fig.no 5.2



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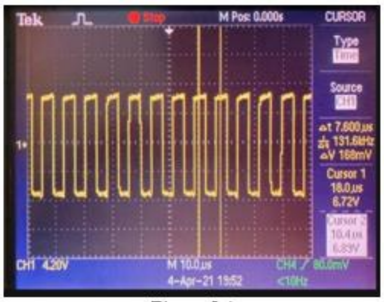

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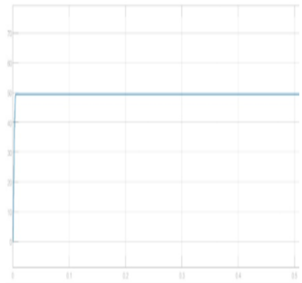

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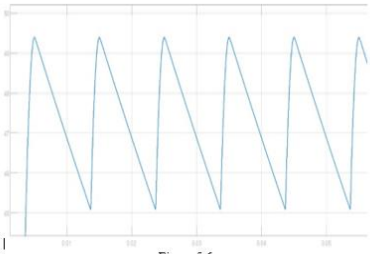

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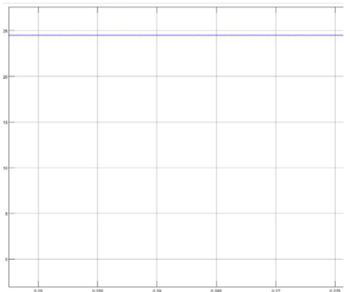

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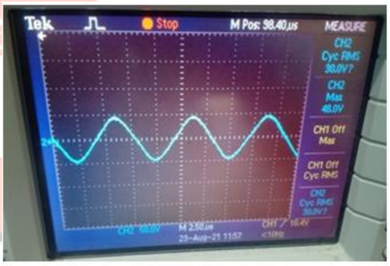

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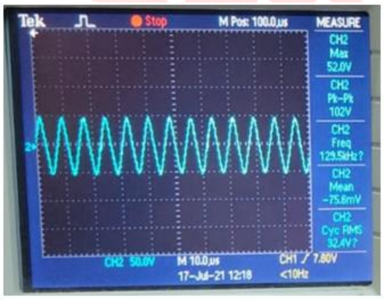


Fig.no 5.9

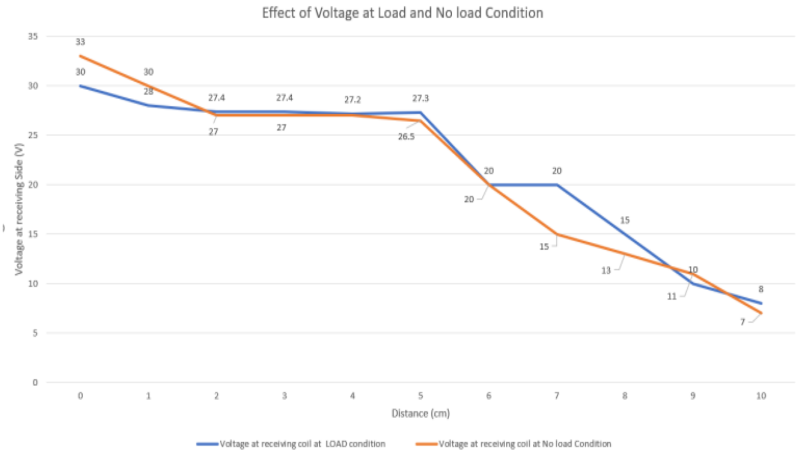
Case 1: Analysis at No - Load condition

Distance	V_{rms} (Transmission side)	V_{rms} (Receiving Side)	Efficiency in wireless transmission	V_{out} (DC)
0 cm	50 V	33 V	66%	24.4 V
1 cm	47 V	30 V	63%	24.4 V
2 cm	44 V	27 V	61.3%	24.4 V
3 cm	44 V	27 V	61.3%	24.4 V
4 cm	43 V	27 V	61.3%	24.4 V
5 cm	43 V	26.5 V	60.6%	24.4 V
6 cm	44 V	20 V	45.45%	1.2 V
7 cm	44V	15 V	34%	1.2 V
8 cm	44 V	13 V	29%	1.2 V
9 cm	44 V	11 V	25%	1.2 V
10 cm	44 V	7 V	15.9%	1.2 V

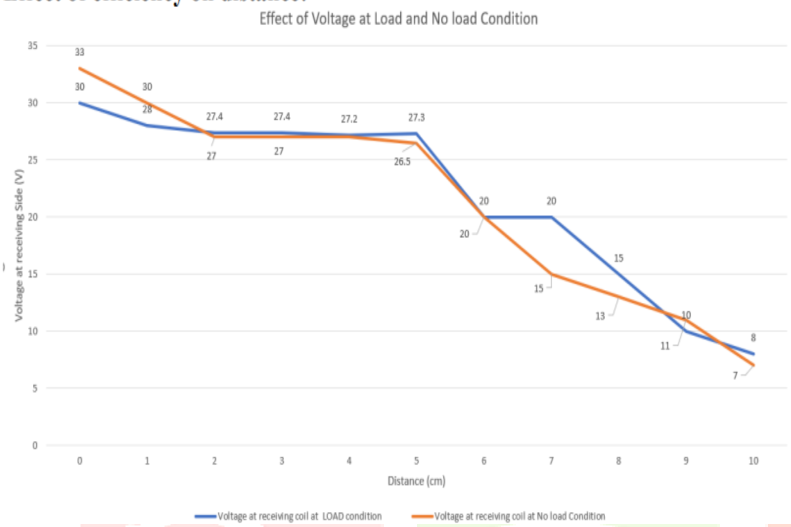
Case 2: Analysis at Load condition

Distance	V_{rms} (Transmission side)	V_{rms} (Receiving Side)	Efficiency in wireless transmission	V_{out} (DC)
0 cm	48 V	30 V	62.5%	24 V
1 cm	48 V	28 V	58.33%	24 V
2 cm	47 V	27.4 V	58.29%	24 V
3 cm	46 V	27.4 V	59.56%	24 V
4 cm	44 V	27.2 V	61.81%	24 V
5 cm	44 V	27.3 V	62.04%	24 V
6 cm	44 V	20 V	45.45%	24 V to 1.2 V
7 cm	44V	20 V	45.45%	24 V to 1.2 V
8 cm	44 V	15 V	34.09%	24 V to 1.2 V
9 cm	44 V	10 V	22.72%	24 V to 1.2 V
10 cm	44 V	8 V	18.18%	24 V to 1.2 V

Effect of voltage on distance:



Effect of efficiency on distance:



VI. ACKNOWLEDGEMENT

Necessary improvements, given the resources, can undoubtedly improve the efficiency significantly a higher frequency would yield a higher efficiency. However, doing so requires certain measures to be taken. Switching losses and coil resistances would increase and needs to be dealt with. High frequency capacitors are also expensive. Use of high frequency IGBTs enable usage of higher power rated inverters. Higher power levels can achieve larger distances of power transfer. Working with higher power levels again calls for the usage of expensive devices capable of handling high voltages and currents.

VII. REFERENCES

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