Magnetic Coupling Resonant Wireless Power Transmission

B. A. Manjunatha, K. Aditya Shatry, P. Kishor Kumar Naik, and B. N. Chandrashekhar

Abstract Every magnetic induction wireless power transfer (WPT) or inductive power transfer (IPT) system operates on the two guiding principles of Faraday's law of induction. A conductor can generate an electromotive force (EMF) that is inversely proportional to the strength and rate of change of the magnetic field when an alternating magnetic field is present, as stated by Faraday's law of induction. A conductor can generate an electromotive force (EMF) that is inversely proportional to the strength and rate of change of the magnetic field when an alternating magnetic field is present, as stated by Faraday's law of induction. Wireless power transmission technology provides a significant advantage over the conventional way of transferring power over a distance. Here, the electrical energy can be transferred wirelessly without using the cables. In this paper, based on the working principle of magnetic coupling resonant wireless power transmission (MCR-WPT), we have designed and analyzed the major circuit with the help of simulation. The simulation of the design is carried out by using Multisim software, and also, the hardware implementation is done.

Keywords MCR-WPT · Faraday's law · EMF

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1 Introduction

Contactless power transmission alias wireless power transmission (WPT) is a new way of transferring power wirelessly through the air or vacuum and can be realized by a load connected across the circuit through electromagnetic field effect [1]. With this technology, it is possible to transfer power to remote areas, which are far away from the cities, where the conventional power transfer through wiring is not easy. Since, the traditional way of power transfer has many challenges such as power loss, expensive cost, efficiency, maintenance.

WPT can provide a much flexible, better coverage, and safety over the wired transmission. WPT is sorted into different types depending on the distance as shown in Fig. 1. The near-field (non-radiative) technique consists of capacitive coupling, inductive coupling, resonant coupling. The far-field (radiative) technique consists of microwaves and lasers [2, 3]. The field stays within a close range from the transmitter in near-field technique, and the receiver is made to be very close to the transmitter to achieve maximum power. If the receiver is not found within the field range, then no power transmission takes place from the transmitter. As the distance increases, the power transmitted gets decreasing. In the far-field technique, prolonged power transmission can be achieved, where the gap is very much larger than the diameter of the device. Maxwell's electromagnetic concept, which was first published in 1865, has made mention of electromagnetic waves that move at the speed of light and reached to the conclusion that light itself was just such a wave. In 1886, Hertz conducted an effective study on the transmission of pulsed wireless energy. He built an apparatus that could produce and pick up UHF microwaves.

Practically speaking, there are still issues that require immediate attention. The charging distance between transmission and reception will vary since the chassis heights of electric vehicles vary. The effectiveness of the same coil system will differ drastically depending on the charging distance, which could affect the power charging that falls short of need. In this situation, the coupling coefficient between the coils needs to be changed. In order to increase efficiency, variable coupling technology was applied for the mechanical construction. Similar differences regarding the coil distance are expected in medical implantable devices such as pacemakers

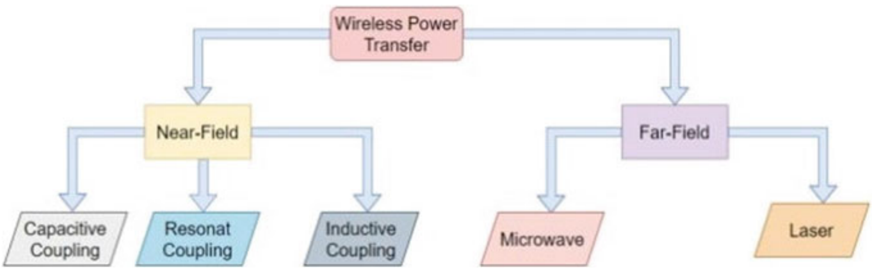

Fig. 1 Classification of WPT

and auditory chips, and the mechanical structure is unsatisfactory. An approach using a reconfigurable helical coil array is suggested in order to overcome the problems with mechanical motion and achieve high-efficiency transmission. A very effective coil with high distance robustness must be built for this. In comparison to the standard four-coil configuration of the same volume, different source and load coils are used at varied distance conditions. The coupling coefficient between the coils is adjusted to maintain transmission efficiency. In addition, a control technique is presented to implement coil switching. Different source and load coils can be chosen by the switching circuit to ensure smooth operation as the distance changes based on magnetically coupled resonant. An emphasis has been placed strategy of both electric energy and signal which is proposed for WPT with the conventional double-coil configuration.

2 Literature Review

Electrical energy can be transmitted wirelessly when no wires or conductors are involved. It is advantageous to move electrical energy to locations where it is challenging to do so with traditional cables. Using the fundamentals of magnetic resonant coupling, we designed and put into practice a wireless power transfer system in this study. For the power transmission efficiency of both receivers, numerical data are supplied. Graphs are provided to compare the power and efficiency of the two receivers as a function of distance [1]. An overview of wireless power transfer research is given. In contrast to conventional power transmission, wireless power transmission can accommodate the demands of advancing science and technology. It is broadly applicable to electronic devices, implantable medical devices, industry, and other industries and is a popular topic for research both domestically and internationally. The history of development, classification, and application domain of wireless power transfer are presented in this study. In this research, a number of wireless power transmission techniques were contrasted. This study focuses on the development trajectory and state-of-the-art of wireless power transfer using magnetic coupled resonance (MCR-WPT) [2]. The efficiency of wireless power transfer (WPT) systems is investigated for both the angular aligned and unaligned orientations of the receiver and transmitter coils. Utilizing Maxwell 3D software, certain equivalent circuit parameters were computed. Through the use of the system's mathematical modeling, the MATLAB programmer calculated the circuit's analytical solution. But PSIM, a program for circuit simulation, was used to derive the system's numerical solution. Additionally, a transient analysis of the three-dimensional system was carried out using Maxwell 3D software and the finite element technique (FEM). The efficiency of the system was roughly determined by calculating the input and output powers. The results demonstrated that power was effectively transmitted in both aligned and unaligned locations to a significant degree. The results also demonstrated that for aligned positions, high efficiency could be achieved with air gaps of 15–20 cm and that efficiency rapidly declined with air gaps greater than

20 cm. At air gaps up to 10 cm, it was discovered that wireless power transmission could be carried out for spatially unaligned sites with acceptable efficiency. However, at air gaps larger than 10 cm, this efficiency rapidly deteriorated [3]. The phrase "wireless power transmission" refers to the long-distance transmission of electrical energy without the usage of conducting wires or cables. The concept of wireless power transfer was developed by Nikola Telsa. Thanks to wireless power transfer, which eliminates the need for conventional copper connections and current-carrying wires, electrical engineering may undergo a considerable change [4]. In comparison to traditional power transfer techniques, wireless power transmission technology offers various benefits. This study presents the basic architecture and operation of magnetic coupling resonant wireless power transfer. The core circuit design and analysis of the transmission system are built on top of this. The success of the future research effort's functional functioning is also noteworthy [5]. Magnetic resonance and coupling the wireless power transfer (WPT) system is a cutting-edge technology that is commonly employed in the medium-distance field. In order to address the frequency-splitting problem in the WPT system, a WPT system with an appropriate Class E inverter construction is demonstrated in this work. A method for monitoring the emission frequency, receiving frequency, and adjusting frequency is shown by the system. Finally, the simulation and experiment results validate the applicability of the proposed control techniques. The final section includes simulation experiment results to demonstrate the practicality of the suggested strategy [6]. There is a quickly expanding interest in wireless power transfer (WPT) for industrial machinery, consumer electronics, and electric vehicles due to growing concerns about the convenience and security of the power supply (EVs). There is a pressing need for researchers to create a high-efficiency high-frequency resonant circuit, particularly for the mid-range near-field WPT system, as the resonant circuit is one of the crucial components of both the near-field and far-field WPT systems. Also discussed are several important topics like total harmonic distortion, zero-voltage switching, and zero-voltage derivative switching. Bidirectional resonant inverters being developed for WPT-based vehicle-to-grid systems as the use of wireless charging for electric vehicles grows [7].

3 Proposed Work

The MCR-WPT uses the resonance principle for the transmitter and receiver to satisfy the resonance requirements and provides the transmitting coil and receiving coil for the equal resonant frequency, providing the efficient energy transmission between the coils and enhancing wireless transmission performance. The most fundamental resonant coupling consists of a primary driving coil and a secondary resonance circuit. Examining the resonant state on the secondary side from the main side reveals two resonances as a pair in this case. Parallel resonant frequency 1 is another name for the anti-resonant frequency, and serial resonant frequency 1' is another name for the resonant frequency (Fig. 2).

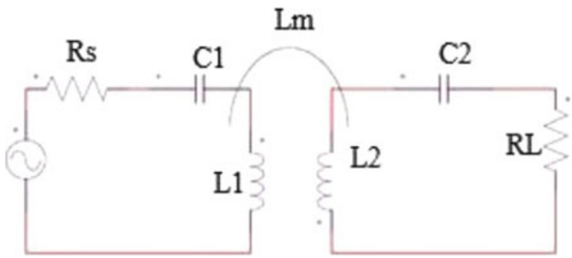

Fig. 2 Equivalent circuit of magnetic resonant coupling [7]

A resonant circuit is created by the secondary coil's resonant capacitor and short-circuits inductance. The primary coil's magnetic field and the secondary coil's magnetic field have synchronized phases when the primary coil is activated with a resonance frequency of the secondary side. The secondary coil produces the highest voltage as a result of the enhanced mutual flux, whereas the first coil's copper loss, heat generation, and efficiency are all significantly decreased. Resonant coupling, which is the near-field wireless transmission of electrical energy, takes place between the magnetically coupled coils that are a part of a resonant circuit tuned to resonate at the same frequency as the driving frequency. The MCR-WPT structure uses the DC power supply as the input, an E-type circuit to act as an inverter, a compensation circuit for resonance, and the transmitting and receiving ends in order to provide high-efficient power transfer for long-distance transmission.

3.1 First, An E-type Inverter

The MCR-WPT structure uses the DC power supply as the input, an E-type circuit to act as an inverter, a compensation circuit for resonance, and the transmitting and receiving end in order to provide high-efficient power transfer for long-distance transmission. The Class E resonant inverter architecture used in the low-voltage electronic fluorescent light ballast aims to improve the EMI, cost, and efficiency of earlier electronic ballast designs. The electromagnetic emissions that are conducted and transmitted are minimized by their sinusoidal current flow. Their small size and lightweight maximize portability, and their single specialized component and low component count maintain cheap unit prices. LCR resonance is used by the inverter to transmit AC power to a load. Using a switching MOSFET and a significant amount of inductance Lf from a DC source, a series resonant circuit is stimulated. If Lf is large enough, it appears that the input to the MOSFET and resonant circuit is a source of current. The voltage gain produced by the series resonant circuit is a function of both its quality factor and magnitude [4]. Any component of the LCR circuit could be a load or the parasitic features incorporated into the switching device. The MOSFET's body diode allows a load with variable resistance to operate in a state referred to as a sub-optimal mode. The E-type inverter is often used in low-power applications [6] and only requires one low switching loss transistor. This inverter's output voltage is

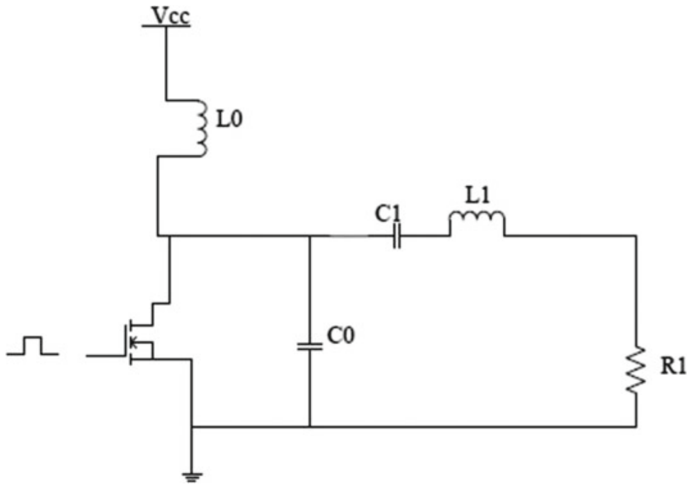

Fig. 3 Class E inverter [6]

fixed, yet the varying switching frequency may cause it to alter. The inverter circuit converts the input DC to AC. It is regarded as the optimum architecture for driving circuits due to its great efficiency and simple design. There is only one inverter control circuit on it. The Class E inverter construction is shown in Fig. 3. Utilizing wireless power transfer, power is delivered to the load without any mechanical connections between them (WPT).

3.2 Compensation Structure

To transmit power to the load, the coupled inductors in wireless power transfer (WPT) are not mechanically attached. The compensation circuit of the resonant converter is the primary factor affecting the WPT system's productivity. Compensatory circuits come in four varieties: SS, SP, PS, and PP (Fig. 4). Other topologies are less suitable for adequate long-distance transmission than the SP circuit, which connects one inductor in series to the primary-side network and the other in parallel at the secondary side network. Series compensation is especially the compensation capacitors which are arranged in series along the track; they are well suited for systems with lengthy primary tracks. This enables the track voltages to be controlled within the authorized upper limits. Since they are usually high current systems, concentrated windings are a better suited for the parallel compensation. A single capacitor is used at the coil's terminals. When considering the requirements for capacitors, the series compensation indicates higher voltages and lower currents than the parallel compensation. The primary-side capacitance affects the input-to-output voltage ratio of the resonant circuit of the SP architecture, which consists of compensating capacitors

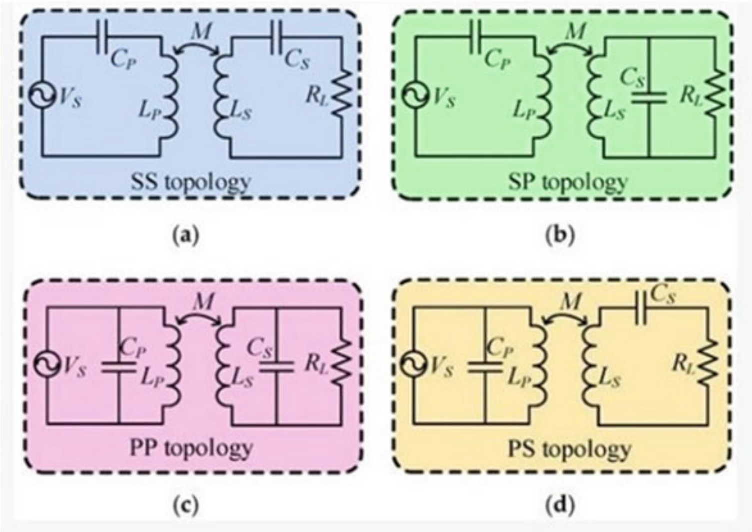

Fig. 4 Compensation structure [9]

and two coils. As a result, the primary-side capacitor's capacitance has an impact on overall efficiency, which has an impact on the inverter and resonant circuit efficiencies as well. Due to its highest efficiency, SS and SP compensations are utilized most commonly in real applications. Compensations utilizing a parallel capacitor on the primary side are rarely used because of the high input impedance, difficult calculations, reliance on the coupling coefficient and load, and other problems. Nevertheless, other sources assert that all semiconductor devices feature gentle switching thanks to the PS compensation mechanism.

The main advantage of the SS topology is that the compensatory capacities are not dependent on the magnetic coupling coefficient or the resonance frequency of the load. For a strong magnetic coupling, the SP topology, on the other hand, requires a higher primary capacity and is coupling factor dependent.

The primary capacitance calculations for the PS and PP topologies of two additional parallel primary compensating capacitors are significantly more complex. Changes in the load resistance and the coupling factor also have an impact on the resonance capacity's value.

In order to improve inverter current management (transformation into inductance–capacitance–capacitance (LCC), CCL, etc.) flowing in the parallel resonant circuit and boost PS and PP efficiencies, the topology requires additional serial inductance. This inductance raises the price and converter size of the system.

The requirement of the current source input to prevent any abrupt change in the voltage is another issue. Another crucial element is the input resistance value, which is particularly high in PS and PP topologies. To transfer the necessary quantity of power, this needs a high driving voltage. The voltage gain in the PP topology depends on the parameters of the load and the transformer at the resonance frequency, and it is always less than 1. Depending on the load, the voltage ratio will display a varied value. With greater coupling or a higher secondary quality factor, a smaller primary capacitance is always needed for PS topology, and the change gets larger. Due to the parallel primary's high current source requirements, the parallel secondary's high load voltage, and the PP configuration's low-power factor, these factors are detrimental. The high efficiency, high power factor, relatively low mutual inductance, and a sizable load variation and mutual inductance range are the key benefits of the PS and PP topologies. The coupling coefficient and, consequently, mutual inductance will have to be relatively low values in order for the efficiency to be acceptable. More voltage and current are needed for the series compensation than the parallel compensation.

3.3 Rectifier

Two-way alternating current (AC) that is oscillating is converted to single-directional direct current by rectifiers (DC). Including modern silicon-based systems including vacuum tube diodes and crystal radio receivers, there are many different physical configurations for rectifiers. There is not much hope of setting up your ideal system without the proper rectifier. Given that they provide optimum solutions for each application, they are the brains of a power system. Reducing the need to repair every component of your power system allows you to customize it by using rectifiers.

One phase of AC power is the input for single-phase rectifiers. The structures require just one, two, or four diodes (dependent on the type of system). This indicates that the single-phase rectifier has a low transformer usage factor and delivers a little amount of power (TUF). A single-phase rectifier connects diodes to the single-phase transformer's secondary winding and converts only one phase of the secondary coil. The ripple factor is significant as a result. An input for three-phase AV power is used by three-phase rectifiers. Three or six diodes are required by structures, and these are connected to each phase of the secondary winding of the transformer. Three-phase rectifiers are used in place of single-phase rectifiers to reduce the ripple factor. Three phases are preferred over the other two types of rectifiers when using large systems. This is because they have a high output power and do not require a separate filter to reduce the ripple factor. Therefore, three-phase rectifiers are more efficient and use more of the available transformer power. Half-wave rectifiers provide pulsating DC output from one and a half AC cycle input. By blocking the other half of the AC input cycle, this only permits one cycle to pass. Positive or negative half cycles are also possible. There is only one diode utilized, making it the simplest rectifier. Figure 1 illustrates a positive half-wave rectifier; in contrast, a negative half-wave rectifier would demonstrate reverse bias in the diode (facing the opposite way). The direct current is pulsating; therefore, the ripple factor is significant. As a result, half-wave rectifiers are not seen to be efficient and frequently require filters to lower the ripple factor. Direct current (DC), which travels in a single direction, is produced

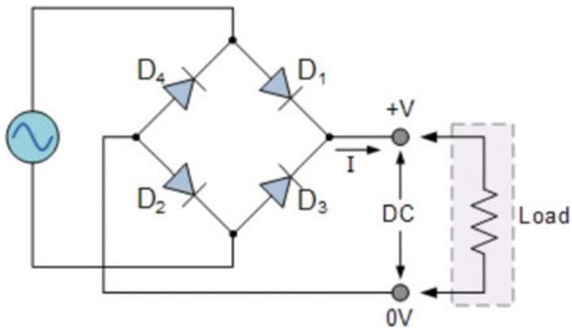

Fig. 5 Full-wave bridge rectifier [2]

when a rectifier changes alternating current (AC), which regularly changes direction. It is frequently used to supply the required DC voltage because the full-bridge rectifier (Fig. 5) is more effective than the half-wave rectifier and operates with both positive and negative half cycles of the AC. A circuit known as a filter is used to modify, restructure, or reject any undesirable high-frequency signals while allowing just the desired signals to pass. The passive RC low-pass filter only lets through low-frequency signals between 0 Hz and its cut-off frequency. A "first-order filter" or "one-pole filter" is a filter that takes an input signal and applies it to a series combination while taking an output signal and passing it across a capacitor. No matter what changes in the input voltage, the voltage regulator produces a constant output voltage. The results produced by the IC 7812 are superior to those of other rectifier ICs.

When there are only diodes in the circuit, uncontrolled rectifiers result. Up to this point, we have only discussed uncontrolled rectifiers. Thyristors are used to regulate the DC output in controlled rectifier circuits. Since diodes may only be turned on or off, these are employed when precise current control is required. Continuous control is possible and no power is wasted with controlled rectifiers.

3.4 Filter

A circuit known as a filter is used to modify, restructure, or reject any undesirable high-frequency signals while allowing just the desired signals to pass. By stringing together in series a single resistor and a single capacitor, as shown in Fig. 6, it is straightforward to construct a passive, RC low-pass filter, or LPF. The input signal (VIN) is applied to the series combination while the output signal (VOUT) is taken across the capacitor alone in this type of filter setup (both the resistor and capacitor together). For real-ongoing applications, the ideal filter must typically be approximated because it cannot be realized without also having signals of indefinite length in time.

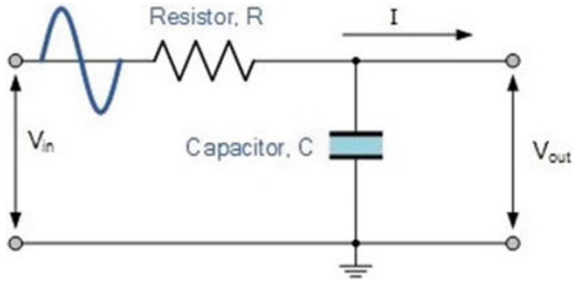

Fig. 6 RC low-pass filter [7]

As the sync function's support zone includes all past and future timeframes, it typically needs to be approximated for genuine continuous signals. Therefore, in order for the filter to complete the convolution, it would need to have infinite delay or infinite knowledge of the past and future.

The reason this form of filter is referred to as a first-order filter or one-pole filter is because it only contains one reactive component in the circuit, the capacitor. A capacitor's reactance varies inversely with frequency, but the value of a resistor does not change as the frequency changes. When compared to the capacitor's capacitive reactance, (XC), the resistor's resistive value, R, will be very low at low frequencies.

An integrated circuit that is self-contained and fixed linear in terms of voltage regulation is the 7812 voltage regulator. The voltage regulator family of the IC 78xx includes the IC. The 7812 voltage regulator IC is inexpensive and simple to use. The output voltage of 7812 is shown by the last two numbers, which are 12 V.

This suggests that the voltage potential, VC, generated across the capacitor will be substantially greater than the voltage drop, VR, generated across the resistor. At high frequencies, the opposite is true, with VC being small and VR being big, as a result of the variation in capacitive reactance value. The circuit above can be thought of as a frequency-dependent variable potential divider in addition to its role as an RC low-pass filter.

3.5 Voltage Regulator

A system that automatically keeps the voltage constant is called a voltage regulator. A voltage regulator could either have a straightforward feedforward architecture or negative feedback. Electronic components or an electromechanical mechanism could be used. It might be utilized to control one or more AC or DC voltages depending on the design.

The processor and other components' DC voltages are regulated by electronic voltage regulators in devices like computer power supplies. Regulators of voltage control the plant's output in alternators for automobiles and centralized power systems. A voltage regulator can be installed at a substation or along distribution lines in an electric power distribution system to guarantee that every customer receives

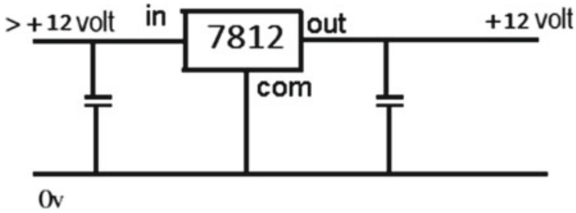

Fig. 7 7812 voltage regulator [8]

a constant voltage regardless of how much power is drawn from the line. The self-contained fixed linear voltage regulator integrated circuit known as the 7812 voltage regulator regulates voltage. The voltage regulator family of the IC 78xx includes the IC. The 7812 voltage regulator IC is inexpensive and simple to use. The output voltage of 7812 is shown by the last two numbers, which are 12 V.

Because the IC 7812 is a positive voltage regulator, it produces positive voltage with regard to common ground. (Fig. 7).

The 7812 voltage regulator IC and the 7912 IC from the 79XX series are combined. The TO-220, TO-3, TO-92, and surface mount packages are the most prevalent in which the voltage regulator 7812 is offered. The input voltage and current must be at least 2.5 volts and 1 or 1.5 amps higher than the output voltage, respectively, for the IC 7812 voltage regulators to function at their best capacity. For the various IC Packages the voltage and current differential is different.

4 Design of Circuits

The MCR-transmitter WPT's and receiver circuits were created via simulation (Fig. 8).

The switching frequency of the inverter circuit is assumed to be 17 kHz for a 12 V DC input. The equation can be used to determine the transmitter circuit's L_1 and C_1 components (Fig. 9).

$$L_1 = 0.4001 * R/ws, \tag{1}$$

$$C_1 = 2.165/R * ws. \tag{2}$$

Copper will be ideal to produce resonant coils because of its low resistance. To get the greatest flux linkage, the number of turns and area of the coil can be varied. Assuming the C and value, the L value in the compensation system can be calculated by:

$$L = 1/w^2 * C. \tag{3}$$

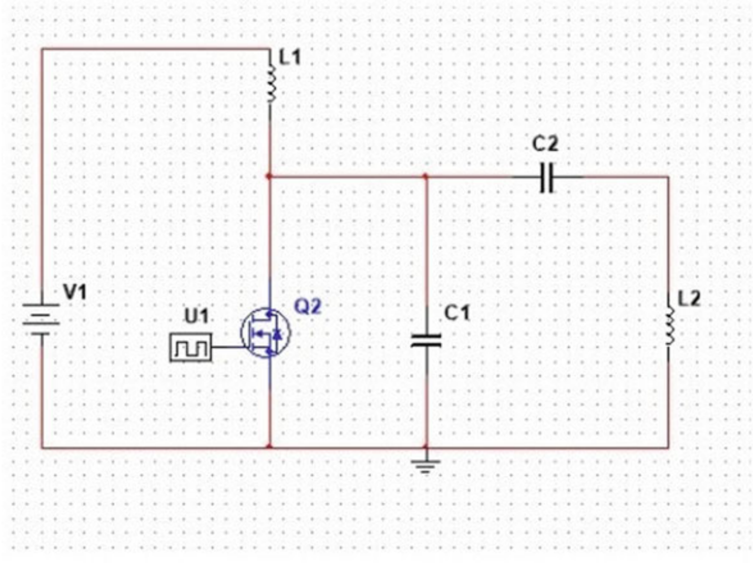

Fig. 8 Transmitter circuit

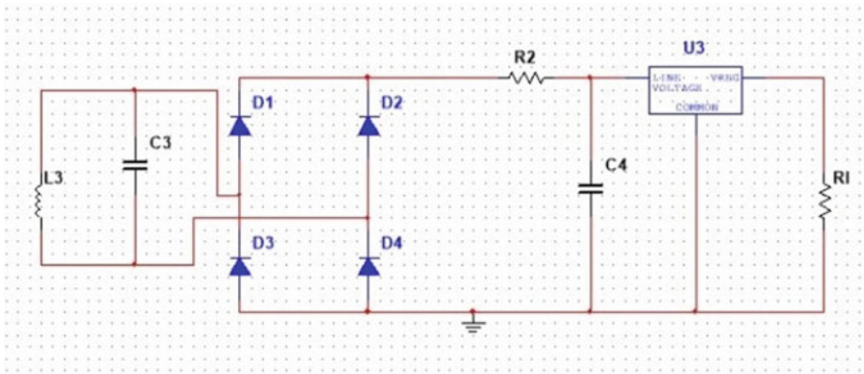

Fig. 9 Receiver circuit

The inductor and capacitor values of the primary and secondary sides are taken the same, i.e., $L_2 = L_3$ and $C_2 = C_3$, and the mutual inductance between two coils is given by:

$$M = \mu_0 * \mu_r * N_1 * N_2 * A/L. \tag{4}$$

Coupling coefficient is given by:

$$k = m/\sqrt{L_1 * L_2}, \tag{5}$$

$$V_c = \frac{1 * V_{in}}{1 + R_c}. \tag{6}$$

And across the resistor is:

$$V_r = \frac{R_c \ * \ V_{in}}{1 + R_c}. \tag{7}$$

The efficiency of the circuit is given by:

$$\eta = \frac{P_{out}}{P_{in}} * 100, \tag{8}$$

where

$$w = 2\Pi \ * \ f. \tag{9}$$

f is the resonant frequency.

$$\mu = \mu_0 * \mu \, \mathrm{rH/m}, \tag{10}$$

$$\mu_0 = 4\Pi * 10^{-7} \, \mathrm{rH/m}. \tag{11}$$

5 Results and Discussion

For an input of 12 V, the output power of around 5 W and output voltage of around 7 V is obtained. The graph shown above indicates an output DC voltage of 7 V. The x-axis here represents the time axis and the y-axis represents the voltage axis. We have implemented either the hardware where an LED is glow to a distance of about 4 cm and the brightness reduces and diminishes finally, as the distance between the transmitter coil and receiver coil increases. Here, an output voltage of around 4 V is obtained for the distance of about 4cm. The WPT system is gearing up to impact the community with a much wider influence of science and technology. With the paucity in demand for fossil fuels and as society is moving toward electric vehicles (EVs), there will be a great help by the WPT technology in charging the EVs. In this paper, we have presented an MCR-WPT technology where the power transmission mainly takes place through resonance. By the simulation carried out through the Multisim platform, output power of around 5 W is attained (Fig. 10).

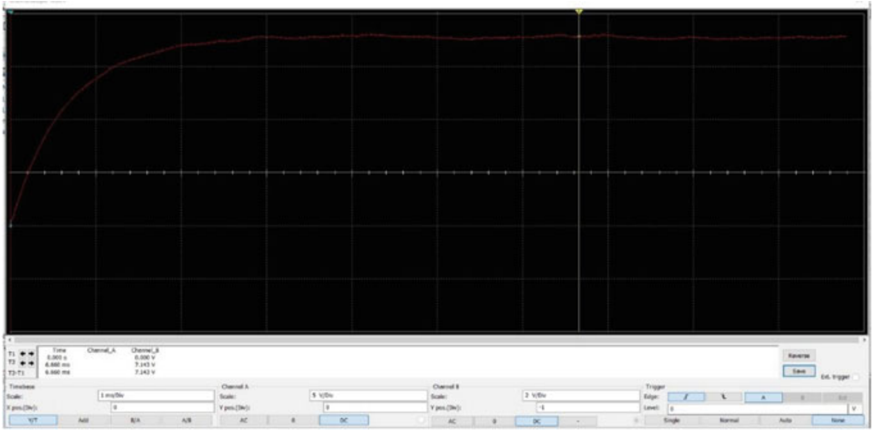

Fig. 10 Simulation result graph

Fig. 11 Hardware implementation

In the simulation result, at initial there will be slow increasing; after the some interval, we got the constant wave which is nearly equal to the 7 V at the Multisim platform (Figs. 11 and 12).

5.1 Wireless Power Transmission Applications and Development Prospects

A. *Electric vehicle wireless charging technology*

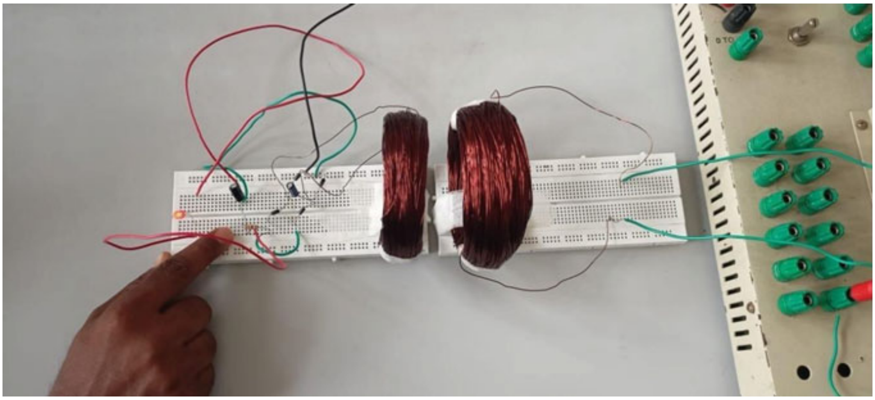

Fig. 12 Hardware implementation

The smart grid's essential elements are electric automobiles, which can also function as energy storage devices due to their size. The wireless charging technology for electric vehicles allows for flexible and safe charging that can substantially lessen the load on the power grid and spread out the charging period. This technology is crucial to the long-term growth of the smart grid. There are numerous research teams both in China and abroad. For instance, the University of Auckland, a New Zealand-based company, has used this technology to charge electric passenger vehicles. Their scholars designed and verified the equivalent circuit model of the MCR-WPT, and the final experimental data reveal that the system's transmission distance is 30 cm and its output power is 220 W, which are the key transmission parameters for wireless charging systems for electric vehicles. The maximum machine efficiency is 90.5%, output power is 3.3 kW, and transmission distance is 20 cm.

B. *Medical equipment*

One of the key areas of study for the use of medical equipment is WPT. It is mostly used to wirelessly charge implantable medical devices as cardiac pacemakers, nerve simulators, artificial hearts, cochlear implants, and retinal prosthetics, among others [12–14]. The following are some benefits:

(1) Because there is no physical connection in the power supply, there is no direct wire-to-skin contact, which reduces the risk of infection-related issues.
(2) The absence of a physical connection to the power source prevents skin-to-wire contact.
(3) Fix the implanted battery power loss after surgery to replace the issue and enhance the patient's post-operative quality of life.

C. *Smart home*

In recent years, the concept of the "smart home" has become more and more relevant as solutions to the problems caused by the restrictions of conventional charging connections are put forth. Mobile phones, laptop computers, wireless charging stations, and free battery wireless mice are a few examples.

D. *Industrial applications*

For items like chemical equipment, detecting tools, underwater robotics, distributed sensor power supply concerns, etc., wireless power transmission technology is occasionally utilized in the industrial sector [15]. The device's high electricity consumption, which occurs when it is commonly utilized in battery mode or cable transmission, has made regular use and maintenance of the equipment particularly challenging. Recently, domestic and foreign academics, corporations, and businesses have become very interested in the wireless power transmission technology as a solution to these problems.

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