Digital Communication Control Application Involving Wireless Power Transmission for Charging Electric Vehicles

EMMANUEL T. EKE[1,3], EMENIKE C. EJIOGU[1,2,3], CANDIDUS. U. EYA[1,2,3,*]
[1]African Centre of Excellence for Sustainable Power and Energy Development,
University of Nigeria,
Nsukka,
NIGERIA

[2]Electrical Engineering Department,
University of Nigeria, Nsukka,
NIGERIA

[3]Laboratory of Innovative Electronics,
Power Devices and New Energy Systems (LIEPNES),
NIGERIA

Corresponding Author

Abstract: - This paper presents a digital communication control application involving wireless power transmission for charging electric vehicles. In the development of electric vehicle (EV) charging systems, wireless charging plays a crucial role. This is due to the rise of self-driving automobiles and significant advancements in artificial intelligence. The majority of studies in this field use induction charging, while others use magnetic resonance. The proposed system is simulated and modeled in MATLAB/SIMULINK using state-space equations. The system architecture employs the inductor-capacitor-capacitor-capacitor (LCC-C) compensation topology. A 32-bit microcontroller ESP32 was used to facilitate communication between the transmitter and receiver. The receiver used a digital signal to start and stop charging, checked the energy level, and kept track of the EV tag for future ways to pay for energy. The project was designed and implemented to charge a lithium battery with a capacity of 55,000 mAh across a distance of 6 cm at 77.52% efficiency.

Key-Words: - Electric Vehicle, LCC-C compensation, Magnetic resonance, Receiver, Transmitter, wireless power transmission.

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1 Introduction

Most power transmission systems use cables, [1]. This gives rise to disadvantages such as aging, wear, the production of an electric spark, and difficulty in transmitting electricity in such places as a mountaintop, seabed, [2], [3], etc. Around the world, a variety of applications have implemented wireless power transfer to eliminate the last cable, [4]. These applications use a wide range of power levels, from sub-watt surgical devices to watt-level commercial gadgets to kilowatt electric cars (EV), [5], [6], [7]. The need to overcome the adverse effects of petroleum products (such as global warming, greenhouse effects, air pollution, etc.) as the primary sources of energy in the transportation demand cycle has made electric vehicles (EVs) a viable replacement for the current transport system, [8], [9], [10]. Electric vehicles are a green form of transportation that helps to minimize greenhouse gas emissions, [11], [12]. This is because EVs make use of alternate and renewable forms of energy, [13]. These energy forms are put into EVs utilizing plug-in chargers, inductively coupled charging, magnetic resonance charging, etc., [14], [15]. Also, the Wireless Power Transmission (WPT) method for charging the EV battery is utilized to remove the shortcomings of wired Electric vehicle battery chargers during some climatic circumstances such as the rainy season and winter, [16], [17]. The charging system of EVs can further be categorized into two, static charging as well as variable (dynamic) charging, [18]. Charging in a static state of EVs is utilized while the vehicle is parked at a place. This can employ either the plug-in system of charging or wireless power transfer, while the dynamic charging system involves only wireless power transfer. Dynamic system of charging allows the powering of moving vehicles, [19]. Static charging is less expensive than dynamic charging, but it requires larger batteries to store more energy. Dynamic charging makes use of several charging coils paved in the road at a distance apart, allowing for the charging of multiple vehicles at the same time. Dynamic charging has the advantage of avoiding the drawbacks of large batteries. This decreases the price of the battery. The wireless charging system has some advantages over the wired transmission of power. In wired power transmission, losses occur due to the resistance of wires during transmission, [20]. A wired system of charging also causes tripping hazards. People may forget to charge and consequently run out of battery power. The cost of the wires used for transmission is high. Transmitting electricity wirelessly minimizes cost [21] and losses and maximizes efficiency. It also facilitates the transmission of electrical energy without the need for physical connections, [22].

There are already existing works in wireless power transfer; this section looks at some of the contributions of these works. Wireless power transmission, through intensely fixed magnetic resonance was proposed in [23]. Exploring non-radiative magnetic resonant induction at Megahertz frequency helped them find the tightly coupled magnetic resonance. They were able to transmit 60W across 2m. Over this distance, they achieved a 15 percent overall wall-to-load efficiency, a value lower than ideal for many practical applications. Magnetically coupled resonators: analysis, experimental results, and range adaption were also proposed in [24]. The work used a method that permits a specific load receiver to be relocated to practically any location and/or orientation within the transmitter's range while maintaining for a span of 0-7cm, a fairly close performance of above 70 percent is achieved. It does not incorporate digital communication mechanisms focusing instead on theoretical modeling of resonant coupling. In [25], “Strong magnetic coupling as a potential way of transmitting power wirelessly to many small receivers” was proposed. The work demonstrated the transfer of power from a single resonant supply coil to numerous resonant receivers, with a focus on the resonant frequency separation difficulties that emerge in multiple receiver systems. It showed that solitary or numerous receivers can be modeled with a basic circuit model. The system’s complexity grows quadratically with the number of receivers making the design and modeling of such a system increasingly challenging. Power control and loading for A megahertz wireless power transfer (WPT) system driven by a high-frequency Class E Power Amplifier (PA) were presented in [26] .The research looked at a 6.78 MHz wireless power transmission system powered by a class E power amplifier. The research developed a control method that maintains high system efficiency in the face of uncertainty and multiple power demands; the maximum measured system efficiency was 72.1 percent at a load power level of 10W but has to deal with on/off control limitations. [27] addressed the emerging and highly relevant challenge of dynamic wireless charging for electric vehicles (EVs), a promising technology to extend EV range and reduce battery size but focused primarily on lane keeping and alignment optimization, leaving out other challenges associated with dynamic wireless power transfer, such as energy efficiency under different driving conditions or infrastructure cost implications. According to [28] analytical computation of mutual coupling between two misaligned rectangular coils with rectangular cross-sections in wireless power applications was proposed**.** They introduced an analytical model for calculating mutual inductance (MI) between misaligned rectangular coils, addressing various layouts, including coaxial alignment, lateral misalignment, rotational misalignment, and their combinations. The uniform current density assumption and the omission of overlapping scenarios limit its applicability to certain real-world cases. [29] investigated the use of ferromagnetic materials (ferrites) to enhance the Power Transfer Efficiency (PTE) of wearable Wireless Power Transfer (WPT) systems, addressing the challenges posed by human body interference. The performance of the proposed system is evaluated at 26 different body locations, providing comprehensive insights into the effects of human body placement on efficiency. However, no clear-cut information was given regarding the transmitter and receiver. This paper proposes exploiting digital communication between transmitter and receiver to control wireless power transmission for static charging of electric vehicles. Communication between the transmitter and the receiver is achieved using ESP32, a 32-bit microcontroller (MCU) that has wireless file capabilities of up to 2.4MHz in terms of frequency. Harnessing this communication control tool ensures that such questions as: are there available charging stations in a network of transmitters and receivers? Is the car in a charging station eligible to be charged? How many cars have successfully completed charge in a day in each station? Are they adequately answered? The digital control features of the microcontroller allow for the integration of multiple charging points into a scalable network, suitable for large-scale deployment. The integration of wireless power transmission and digital communication leads to a hybrid system where electric vehicles are charged and communicate simultaneously, reducing infrastructure costs and improving user experience. The system incorporates an LCC-C compensation topology for enhanced efficiency and power stability. With an emphasis on the design process, magnetic resonance is employed. Magnetic resonance coupling cordless transmission of power is extremely effective for low or medium-power wireless power transmission (WPT), and compensation capacitors are used to tune the source and sink coils in resonant frequency, [30].

2 Model of Magnetic Resonance System

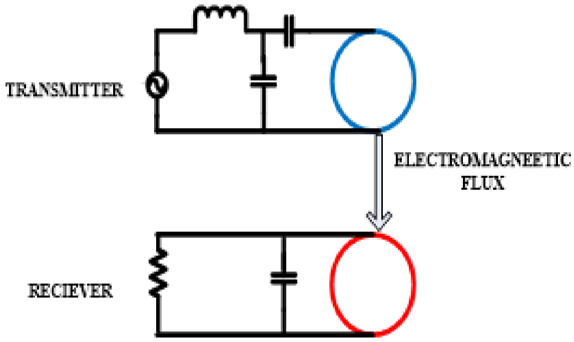

Fig. 1: Magnetic Resonance Circuit

Magnetic resonant wireless power transmission (WPT) is the process of transferring electromagnetic flux from a transmitting coil to a receiving coil under resonant conditions employing coupling through an air gap at a high resonant frequency, [31], [32]. The magnetic flux transferred from the transmitter coil ensures that the sink coil is subjected to an alternating current (AC) voltage, [33]. This voltage is rectified and filtered appropriately before being used to charge the Electric Vehicle (EV), [34]. In the design adopted in the proposed, an inductor-capacitor capacitor-capacitor (LCC-C) compensation network topology is used together with a push-pull switching system fired by a discrete component to reduce the number of switches involved and hence an accompanied reduction of losses attributed to such switches. Figure 1 illustrates the concept of magnetic resonance while Figure 2 shows the LCC-C compensation adopted.

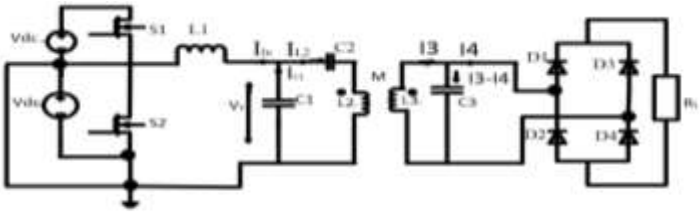

Fig. 2: WPT Magnetic resonance system

3 Model Equations

3.1 Determination of Resonance Frequency using LCC Compensation.

The LCC tuning topology consists of an Inductor and a couple of capacitors for tuning the resonance circuit as shown in Figure 3. The LCC compensation topology with high efficiency also has the advantage of maintaining power transfer from the transmitter to receiver with a certain degree of misalignment.

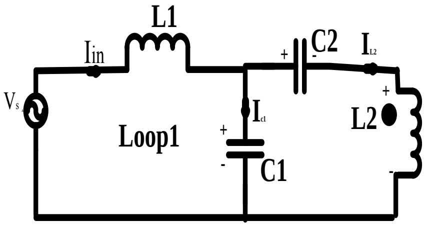

Fig. 3: Transmitter circuit of the magnetic resonance system

The total impedance of Figure 3, Z is given by

$$Z = \left[\frac{\left(\frac{1}{j\omega_0 C_2}+j\omega_0 L_2\right)*\frac{1}{j\omega_0 C_1}}{\left(\frac{1}{j\omega_0 C_2}+j\omega_0 L_2\right)+\frac{1}{j\omega_0 C_1}}\right]+j\omega_0 L_1 \quad (1)$$

where ω_0 , is the resonance angular frequency, C_1 is the capacitance of the transmitter tuning capacitor in parallel with the transmitter coil, C_2 is the capacitance of the transmitter tunning capacitor in series with the transmitter coil, L_1 is the inductance of the transmitter compensation inductor, and L_2 is the inductance of the transmitter coil.

Resolving the impedance, Z into real and imaginary parts and equating the imaginary part to zero will produce.

$$L_1\omega_0 - \frac{1}{(\omega_0 C_1 + \omega_0 C_2 - C_1 C_2 L_2 \omega_0{}^3)} + \frac{(L_2\omega_0)}{(-C_1 L_2 \omega_0{}^2) + \frac{C_1}{C_2} + 1} = 0 \quad (2)$$

Solving for ω_0 produce

$$\omega_0 = \pm\sqrt{\left(\frac{(C_1L_1 - \beta + C_2L_1 + C_2L_2)}{(2C_1C_2L_1L_2)}\right)} \quad (3)$$

where β(absolute sum products of capacitance-inductance of capacitors-inductors) is given by:

$$\sqrt{(C_1{}^2L_1{}^2 + 2C_1C_2L_1{}^2 - 2C_1C_2L_1L_2 + C_2{}^2L_1{}^2 + 2C_2{}^2L_1L_2 + C_2{}^2L_2{}^2\ )}$$

4 State Space Modelling of the LCC-C System

The system as shown in Figure 4 was modeled using state space and the following equations were obtained:

$$\dot{I}_1 = -\frac{R_m I_1}{L_1} - \frac{V_{c1}}{L_1} + \frac{V_s}{L_1} \quad (4)$$

$$\dot{I}_2 = \frac{L_3 V_{c1}}{(L_3L_2 - \mathrm{M}^2)} - \frac{L_3 V_{c2}}{(L_3L_2 - \mathrm{M}^2)} - \frac{\mathrm{M} I_4 R_L}{(L_3L_2 - \mathrm{M}^2)} \quad (5)$$

$$\dot{I}_3 = \frac{M V_{c1}}{(L_3L_2 - \mathrm{M}^2)} - \frac{M V_{c2}}{(L_3L_2 - \mathrm{M}^2)} - \frac{L_2 I_4 R_L}{(L_3L_2 - \mathrm{M}^2)} \quad (6)$$

$$\dot{I}_4 = \frac{1}{R_L C_3}(I_3) - \frac{1}{R_L C_3}(I_4) \quad (7)$$

$$\dot{\mathrm{V}}_{C1} = \frac{1}{C_1}(I_1) - \frac{1}{C_1} \quad (8)$$

$$\dot{\mathrm{V}}_{C2} = \frac{1}{C_2}(I_2) \quad (9)$$

where C_1, C_2, L_1, and L_2 are same as defined for equation (1), I_1 is the transmitter input current, I_2 is the transmitter coil current, I_3 receiver coil current, I_4 is the Load current, V_{c1} is the voltage across C_1, V_{c2} is the voltage across C_2, L_3 is the inductance of the receiver coil, R_L is the load resistance, R_m is the resistance of the switch, V_s is the transmitter source voltage, M is the mutual inductance between the transmitter and receiver coils, $\dot{\mathrm{I}}_1$ is the derivative of I_1 of the first order, $\dot{\mathrm{I}}_2$ is the first order derivative of I_2, $\dot{\mathrm{I}}_3$ is the first order derivative of I_3, $\dot{\mathrm{I}}_4$ is the derivative of I_4, $\dot{\mathrm{V}}_{C1}$ is the first order differential of V_{c1}, and $\dot{\mathrm{V}}_{C2}$ is the first order derivative of V_{c2}, $Combining\ equations$ (4), (5), (6), (7), (8), and (9), the state space equation is formed as:

$$\begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \dot{I}_3 \\ \dot{I}_4 \\ \dot{\mathrm{V}}_{C1} \\ \dot{\mathrm{V}}_{C2} \end{bmatrix} = \Bigg| - \begin{pmatrix} -\frac{R_m}{L_1} & 0 & 0 & 0 & -\frac{1}{L_1} & 0 \\ 0 & 0 & 0 & -\frac{\mathrm{M}R_L}{(L_3L_2-\mathrm{M}^2)} & \frac{L_3}{(L_3L_2-\mathrm{M}^2)} & -\frac{L_3}{(L_3L_2-\mathrm{M}^2)} \\ 0 & 0 & 0 & -\frac{L_2R_L}{(L_3L_2-\mathrm{M}^2)} & \frac{M}{(L_3L_2-\mathrm{M}^2)} & -\frac{M}{(L_3L_2-\mathrm{M}^2)} \\ 0 & 0 & \frac{1}{R_LC_3} & -\frac{1}{R_LC_3} & 0 & 0 \\ \frac{1}{C_1} & -\frac{1}{C_1} & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & 0 & 0 & 0 \end{pmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ V_{c1} \\ V_{c2} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} V_s \quad (10)$$

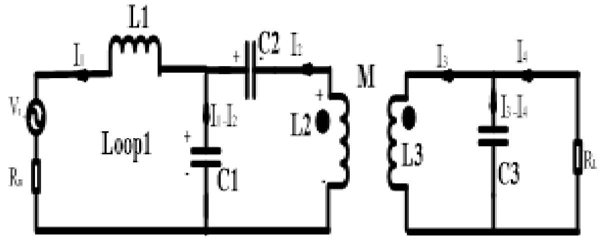

Fig. 4: Modified circuit for WPT Magnetic resonance system

4.1 System Description

The system is described using two different flow charts as shown in Appendix in Figure 5(a) and Figure 5(b). Figure 5(a) in Appendix describes the action taken by the program code for the transmitter section while Figure 5(b) in Appendix displays the program activities of the receiver by the ESP32 microcontroller used for the work.

5 Simulation and Implemented Work Results

After modeling the system in state space, a MATLAB program code was written for the state space equation, and the results obtained are shown in Appendix in Figure 6(a-d). The following parameters were used for both state space and SIMULINK simulations as shown in Table 1 (Appendix).

Figure 6a, 6b, 6c and 6d in Appendix represent supply input, transmitter coil, receiver coil, and load (output) currents respectively. It is observed that the supply input, transmitter coil, receiver coil, and load have 1.2A, 15A, 1.9A, and 1.9A respectively.

The simulation was also carried out using MATLAB Simulink. A Half-bridge inverter system of high frequency was used to produce the firing pulses. These signals were tuned with LCC-C compensation to ensure maximum power transfer at resonant Frequency. The transmitting coil transmits these firing signals to the receiving coil utilizing magnetic resonance. The voltage at the receiving coil is rectified and filtered to power the load. This power ensures digital communication between the transmitter and the receiver. DC output voltage and current of the receiver are as shown in Figure 7 (Appendix).

6 Implemented Work Output

The work was implemented by constructing the transmitter and receiver circuits as well as the battery management unit. 32-bit microcontroller ESP32 was used to generate firing pulses for the switches of the converter circuits and also used for the control system as described in the flow charts shown in Appendix in Figure 5a and Figure 5b. The program enables communication between the transmitter and the receiver due to the wireless file capability of ESP32. This communication helps to locate nearby available charging stations. Determination of energy status (whether the station can adequately charge the EV), start and stop charge through digital signal, and keeping a record of EV tag number for potential energy payment mechanism are other implemented aspects of the work.

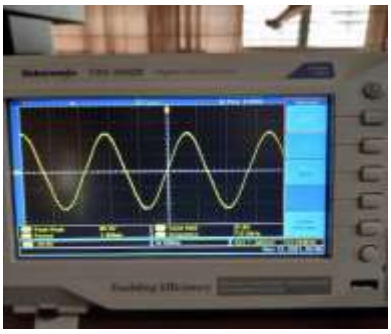

Fig. 8: Experimental Transmitter coil voltage waveform

The project was realized on a scale that charged a lithium battery of 176Wh; 55000mAh. Figure 8 and Figure 9 show oscilloscope results of the transmitter coil voltage waveform and receiver DC output voltage waveforms respectively. Figure 8 depicts the sinusoidal nature of the transmitter coil voltage at an operating frequency of 712 kHz as well as the root mean square voltage of 31.8V. Figure 9 is the DC output voltage waveform which indicates a value of 13V on Load condition. The parameters used for Experimentation in this work are shown in Table 2.

Table 2. Experimental Variables and Parameters

PARAMETER/VARIABLE	**VALUE**	**PARAMETER/VARIABLE**	**VALUE**
Transmitter coil inductance (L_2)	30 µH	Transmitter DC Input Voltage	15V
Receiver coil inductance (L_1)	23µH	Receiver DC Output Voltage on No Load	16.01 V
Mutual Inductance (M)		Receiver DC Output current	1.3
Parallel Transmitter Capacitance (C_1)	220nF	Switch Resistance (R_m)	190mΩ
Series Transmitter Capacitance (C_2)	670pF	Load Resistance (R_L)	170Ω
Receiver Tuning Capacitance (C_3)	670pF	Resonance Frequency(712KHz)	712 kHz
Transmission Distance	2-32cm	Receiver DC Output Voltage on Load	13.5 V

Fig. 9: Receiver DC output Voltage waveform

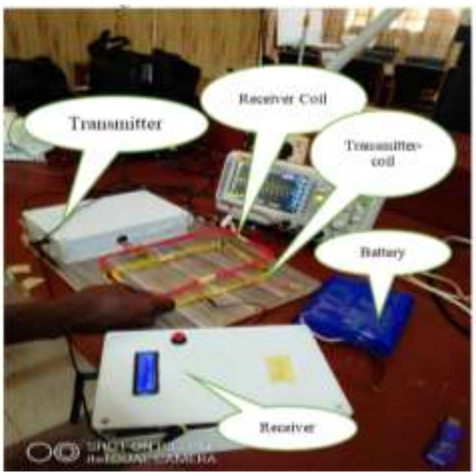

Fig. 10: System setup

With the digital communication control in place, the receiver coil and the transmitter coil will resonate. No output is given out at the receiver to charge the battery till a proper request signal is sent to the transmitter from the receiver. When this is done, access is granted from the transmitter to charge the battery. Also, when the battery is fully charged, appropriate digital signals are interchanged to cut off the battery from charging. The system setup is shown in Figure 10.

7 Result Discussion

Comparing simulation Results and parameters as extracted from Figure 6 and Table 1 in Appendix with those of experimental parameters and results of Table 2 indicates that experimentation is the verification of simulation performed and only varies slightly in certain aspects. The discrepancies between simulation and experimental results presented in the work are attributed to practical constraints and idealized assumptions of simulation. These discrepancies as extracted from Figure 6 and Table 1 in Appendix compared with those of Table 2 are likely due to non-idealities of components such as resistance, inductance tolerance, and parasitic. There are also discrepancies due to imperfect tuning of the LCC-C compensation network and potential alignment during physical setup. Variations in load voltage are related to real-world factors such as circuit imperfection, heat losses, and parasitic effects It highlights the dependency on the alignment of coils, mutual inductance, and power loss during rectification. In addition, the mutual inductance value directly influences energy transfer. Variations in mutual inductance, caused by misalignment or varying distances lead to significant changes in the induced voltage and current, affecting system efficiency and stability.

8 Conclusion

The need to transfer power wirelessly for charging electric vehicles cannot be overemphasized. Digital Communication Control Application Involving Wireless Power Transmission for Charging Electric Vehicles has been presented in this work. This has been made more necessary due to the emergence of self-driving cars and tremendous successes made in artificial intelligence. There is also a great need for control in terms of communication between the transmitter and receiver, determination of energy status, start and stop charge via digital signal, etc. This work presented wireless charging of electric vehicles through the magnetic resonance technique. The concept of using magnetic resonance to statically charge electric automobiles was discussed. The system was modeled using state space equations to determine parameters such as the input current, transmitter coil current, the current flowing through the receiver coil, current flowing through the load, etc. Simulations have been performed using MATLAB SIMULINK to determine the characteristics of load current; load voltage etc. 32-bit microcontroller was used to establish communication between transmitter and receiver which initiates and stop charge through digital signal. The project was implemented to charge a lithium battery of 176Wh; 55000mAh with an efficiency of 77.52% achieved over a distance of 6cm. For future directions and proposals, machine learning algorithms could be deployed to predict and adapt system parameters such as resonance frequency, load resistance, and coil alignment in real-time. This will enhance system reliability and efficiency under varying operational conditi

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APPENDIX

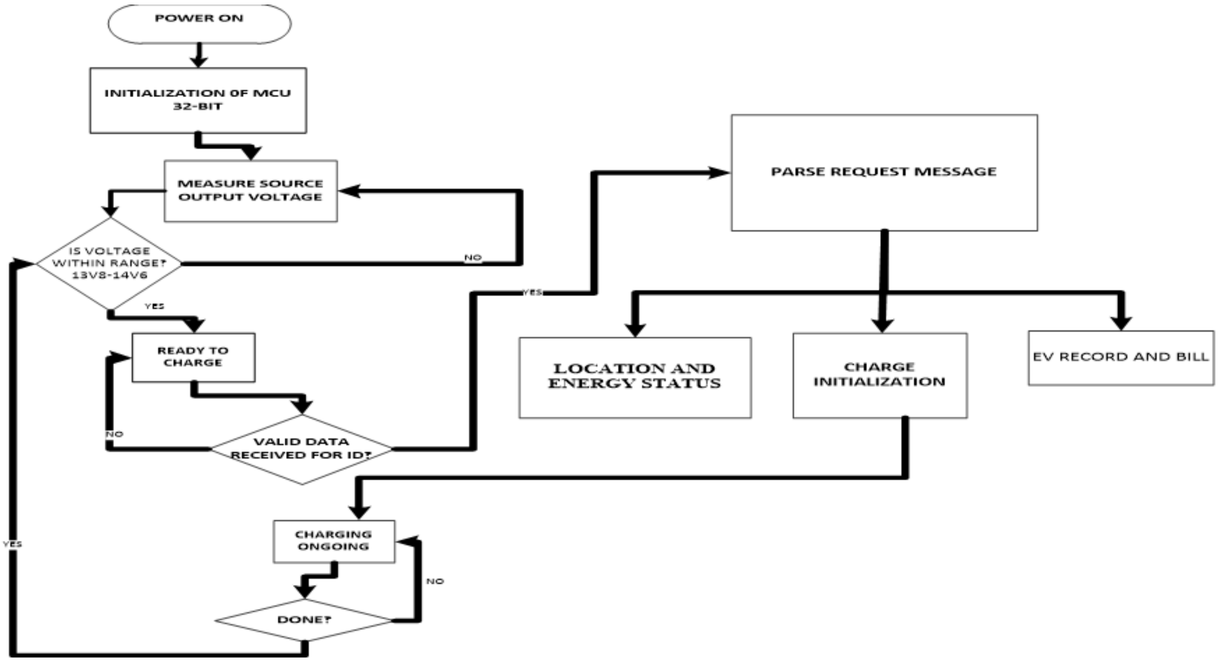

Fig. 5(a): Flowchart for EV Transmitter

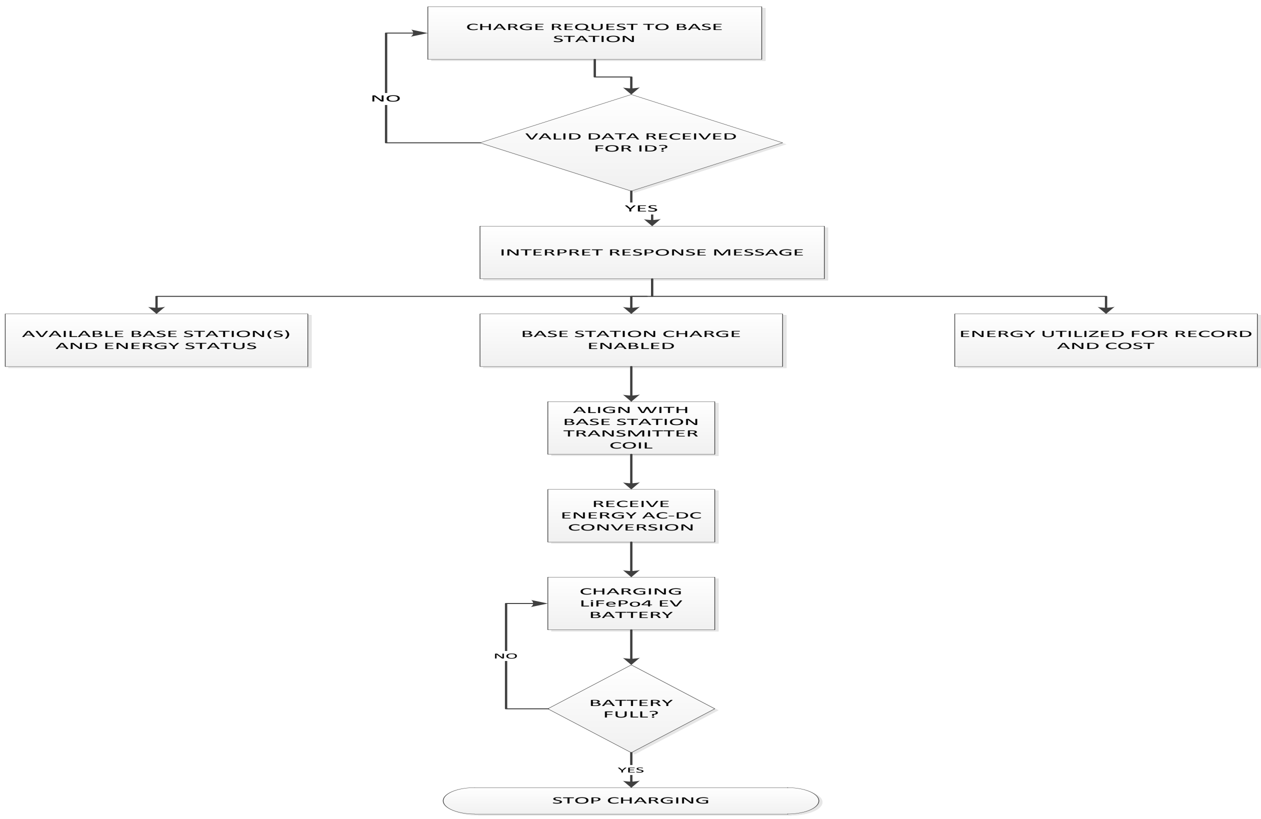

Fig. 5(b): Flowchart for EV Receiver (Sink)

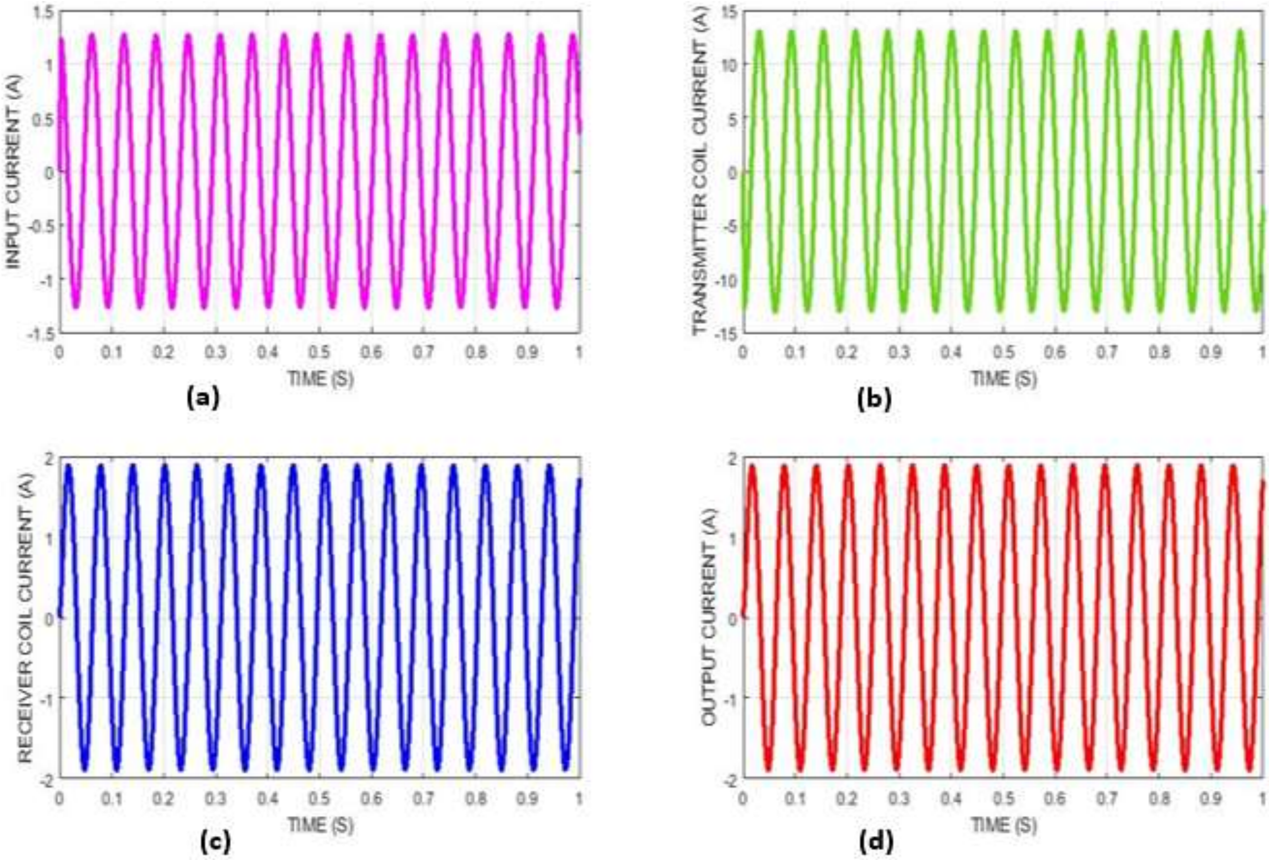

Fig. 6: a) Supply input current, b) transmitter coil, c) receiver coil, d) load (output) current

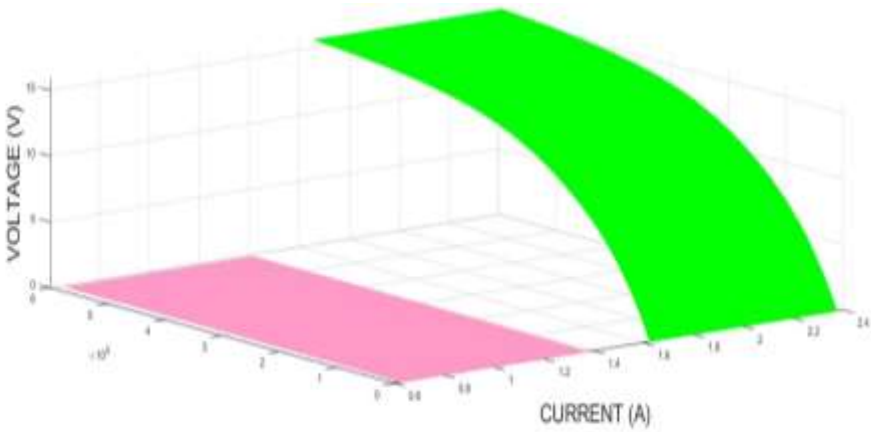

Fig. 7: DC Output Voltage and Current of the Receiver

Table 1. Simulation Variables and Parameters

VARIABLE/ PARAMETER	VALUES
Transmitter coil inductance (L_2) and Receiver coil inductance (L_1)	30 µH and 23µH
Mutual Inductance (M)	24 µH
Parallel Transmitter Capacitance (C_1) and Series Transmitter Capacitance (C_2)	220nF and 670pF
Receiver Tuning Capacitance (C_3)	670pF
Transmission Distance	2-32cm
Transmitter DC input Voltage and Receiver DC Output Voltage	50V and 16.4V
Receiver DC Output current	1.4
Switch Resistance (R_m) and Load Resistance (R_L)	190MΩ and 170Ω
Resonance Frequency	712Hz

Contribution of Individual Authors to the Creation of a Scientific Article (Ghost writing Policy)

- Emmanuel T. Eke conceptualized and implemented different parts of the work. He simulated the work in MATLAB/Simulink software tool.
- Emenike C. Ejioguwas in charge of statistical analysis and overall practical mentoring of the work.
- Candidus. U. Eya played the roles of designing of the system parameters and typographical errors' corrections.

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Conflict of Interest

We (authors) have no conflicts of interest to declare.