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Enhancement of Wireless Powering Process

Abdulkareem Mokif Obais[1], and Ali Faeq Ruzij[2]

[1] *Department of Biomedical Engineering, College of Engineering/ University of Babylon, Iraq.*

[2] *Department Electrical Engineering, College of Engineering/ University of Babylon, Iraq.*

Abstract:

In this paper, related works concerning wireless power transfer (WPT) fields are reviewed taking into account power transmission techniques, transmission distances, inductive coupling strength, efficiency enhancements aspects, and amount of received power. In this work, two WPT systems operating at a resonant frequency of 5 MHz are considered; the first system is built of two planar spiral coils aligned axially and separated by a distance of one meter, while the second system is similar to first one except, it has a third similar coil as resonator located at mid-distance between the two coils. Both systems are designed to energize a 50Ω resistive load. It is verified here that inserting a resonator coil between transmitting and receiving coils very strongly enhance the power transmission efficiency of the proposed WPT system, which is designed and tested on PSpice.

Keywords: Efficiency Enhancement, inductive link, power amplifier, power transfer, wireless power transfer.

I. INTRODUCTION

Wireless power transfer (WPT) means the transmission of electrical power without using connection wires. This technology has achieved significant progresses nowadays at different operating frequencies and for different applications. Some of these achievements are mentioned here. In [1], a WPT system was proposed to transfer a power of 60W at an operating frequency of 9.9 MHz and at power transmission efficiency of 15%. The proposed system was designed to operate within strongly coupled environment at energy transmission distance of 2 meters. A contactless power transfer was introduced by [2] for underwater applications. In this work, a method of reluctance modeling was used to investigate the effects of gap on electromagnetic couples in deep-sea environments. The work conducted by [3] comprised the design of three experimental witricity systems with different geometrical designs. The experimental prototypes for studying the energy transmission between implanted sensors and the external chargers were constructed. In [4], minimization approach of a conical helix was considered for compromising its wideband operation. This was accomplished through coiling its wire along a helical geometry. A WPT system employing inductive coupling method was used to charge electrical vehicles in [5]. In this work, a study concerning all possible topologies for inductively coupled WPTs over air gaps of tens of centimeters had been investigated. Two methods of WPT enhancement were proposed by [6] to improve the power factor and efficiency through presenting several possible solutions until unity power factor correction is achieved. The outcome of the work presented in [7] showed that it is possible to transmit a power of several milliwatt for distance of up to 10 cm utilizing a frequency range of (125-375) kHz. The research presented in [8], describes the effect of the coils parameters on the performance of a certain WPT system. Cylindrical coils were used in the experiments. In this research, the number of turns, radius, and length were changed in steps for each run at different operating frequencies starting from 7.7 MHz to 10 MHz. The magnetic coupling WPT system presented in the research described in [9], used a Class E-amplifier with load resistance of 30Ω. Class E-amplifier was used to drive a WPT system operating at 240 kHz frequency and having an efficiency of 82%. The research described in [10] presented the challenges of producing a low-cost inductively coupled WPT system. In this work, the process of developing a simple factory automation was reviewed. The research presented in [11] describes the biomedical applications of the WPT systems. In this research, spiral printed circuit board technique was used and the system was designed to operate at 13.56 MHz resonant frequency. The research achieved by [12] was to study the wireless power transfer using capacitive coupling to charge a mobile and electrical devices at 6.78 MHz. In [13], a shifting slab technique to enhance the WPT was proposed. The shifting slab was effecting the magnetic field between inductively coupled coils. The experimental work performed by [14], tested the performance of four inductive resonant circuits to achieve the best wireless power transfer. The four systems were series–series, series–parallel, parallel–series, and parallel-parallel. It was verified in this work that the performance of series–series system is better than the other systems when the load is a pure resistive. The work conducted by [15] introduced a satisfactory reviewing of the recent research advances in the area of WPT systems for addressing the challenges facing the perspective research areas. To accomplish these goals, an introduction to WPT systems was presented in this work. In a work conducted by [16], the coherently enhanced WPT system was proposed to control the process of power transfer. The approach depended on the coherent excitation of waveguides connecting the load antenna with a propagating signal at background of certain voltage amplitude and phase.

In this paper, two WPT systems accomplished using magnetically coupled inductive links are considered. The inductive link is simply formed by two coils separated by a certain distance and linked by a magnetic field dependent on their orientation and the distance between them. The energy or power transmission efficiency of the inductive link is inversely dependent on the distance between its coils. One coil of the inductive link is called the sending or transmitting coil, while the other is called the receiving coil. In this work, the power transmission efficiency is strongly enhanced through inserting a third coil known as a resonator between transmitting and receiving coils.

II. THE PROPOSED WPT SYSTEM

The proposed system in this work is designed depending on magnetic inductive coupling method as shown in Fig 1. The system comprised three identical resonant coils, which are the sending coil (L_1), the resonator coil (L_2), and the receiving coil (L_3). Each of the three coils is a planar spiral one wound with 6 turns copper pipe conductor having an outer diameter and wall thickness of 6.35 mm and 0.71 mm, respectively. The inner and outer diameters of the coil are 6cm and 33.5cm, respectively. The length of copper pipe used to wind each coil is 3.72m. The sending coil is energized by a class-E power amplifier for transmitting the AC power during resonance condition, which is achieved by the tuning capacitors C_1 and C_{sh}. Not that the series combination L_1C_1 resonates at a frequency slightly less than the system resonant or operating frequency f_0.The parallel combination formed by L_1C_1 and C_2 resonates at f_0. The system exhibits two series inductive links, which are the first inductive link formed by the sending and resonator coils and the second inductive link formed by the resonator and receiving coils. C_2 and C_3 are the tuning capacitors of the coils L_2 and L_3, respectively. These capacitors are required to achieve resonance at f_0. Each two coils of the proposed system are mutually coupled, thus M_{12}, M_{23}, and M_{13} are the mutual coupling inductances between (L_1 & L_2), (L_2 & L_3), and (L_1 & L_3), respectively.

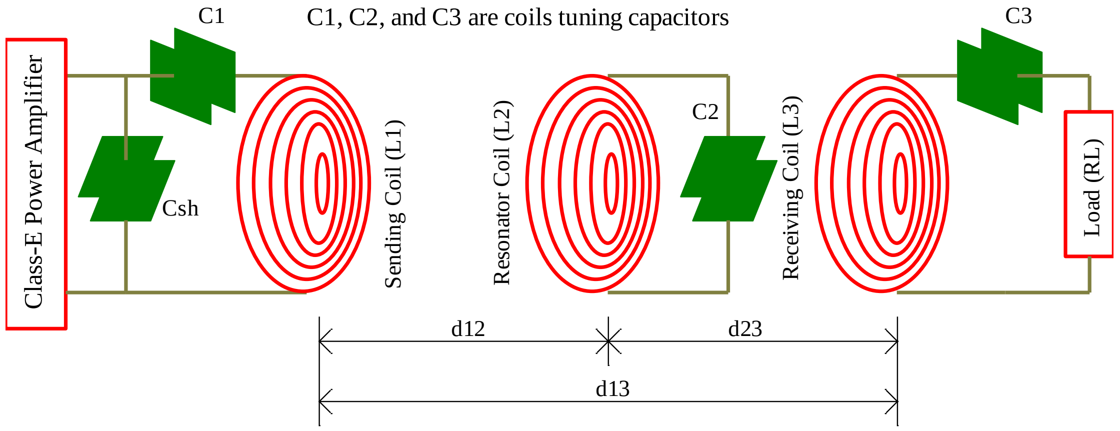

Fig 1. The proposed system.

The mutual inductance M between two planar spiral coils forming an inductive link is given by [17]

$$M = \sum_{i=1}^{N_1}\sum_{j=1}^{N_2}\frac{\mu_0\pi r_i^2 r_j^2}{\left(r_i^2+r_j^2+d^2\right)^{3/2}}\left(1+\frac{15}{32}\gamma_{ij}^2+\frac{315}{1024}\gamma_{ij}^4\right) \tag{1}$$

$$\gamma_{ij} = \frac{2r_ir_j}{r_i^2+r_j^2+d^2} \tag{2}$$

Where, r_i and r_j are the radii of coil turns corresponding to coil one and coil two respectively. N_1 and N_2 are the number of turns corresponding to coil one and coil two respectively. μ_0 is the permeability of free space and d is the axial distance between the two coils. The coefficient of inductive coupling k between the two coils is given by [17]

$$k = \frac{M}{\sqrt{L_1L_2}} \tag{3}$$

Where, L_1 and L_2 are the inductances corresponding to coil one and coil two respectively. N_1 and N_2 are the numbers of turns corresponding to coil one and coil two respectively. The inductance L of a spiral inductor is calculated by [18]

$$L = \frac{0.19685\left((r_{in}+r_{out})N\right)^2}{4(r_{in}+r_{out})+11(r_{out}-r_{in})} \tag{4}$$

Where, r_{in} and r_{out} are the inner and outer radii of the spiral coil, respectively. All dimensions are in cm and the inductance L is determined in μH. The AC resistance R_{AC} of a coil wound with copper conductors can be calculated by [19]

$$R_{AC} = R_{DC}\frac{a}{2\delta_{Cu}} \tag{5}$$

$$\delta_{Cu} = \frac{1}{\sqrt{\mu_0\pi\sigma_{Cu}f_0}} \tag{6}$$

Where, R_{DC} is the DC resistance of the copper conductor and a represents the conductor radius. δ_{cu} and σ_{cu} are copper skin depth and conductivity, respectively.

The equivalent circuit of the proposed system is shown in Fig 2. In this figure R_1, R_2, and R_3 are the AC resistances of the coils L_1, L_2, and L_3, respectively. The mutual inductances between coils, coupling coefficients, coil inductances, and coil AC resistances are calculated according to (1), (3), (4), and (5), respectively. If each two adjacent coils are 50cm apart (i.e. $d_{12}=d_{23}=0.5d_{13}$), then the proposed system parameters are calculated at a resonant operating frequency of 5 MHz and listed in Table 1. Note that d_{12} represents the distance between sending and resonator coils, d_{23} represents the distance between resonator and receiving coils, and d_{13} represents the distance between sending and receiving coils.

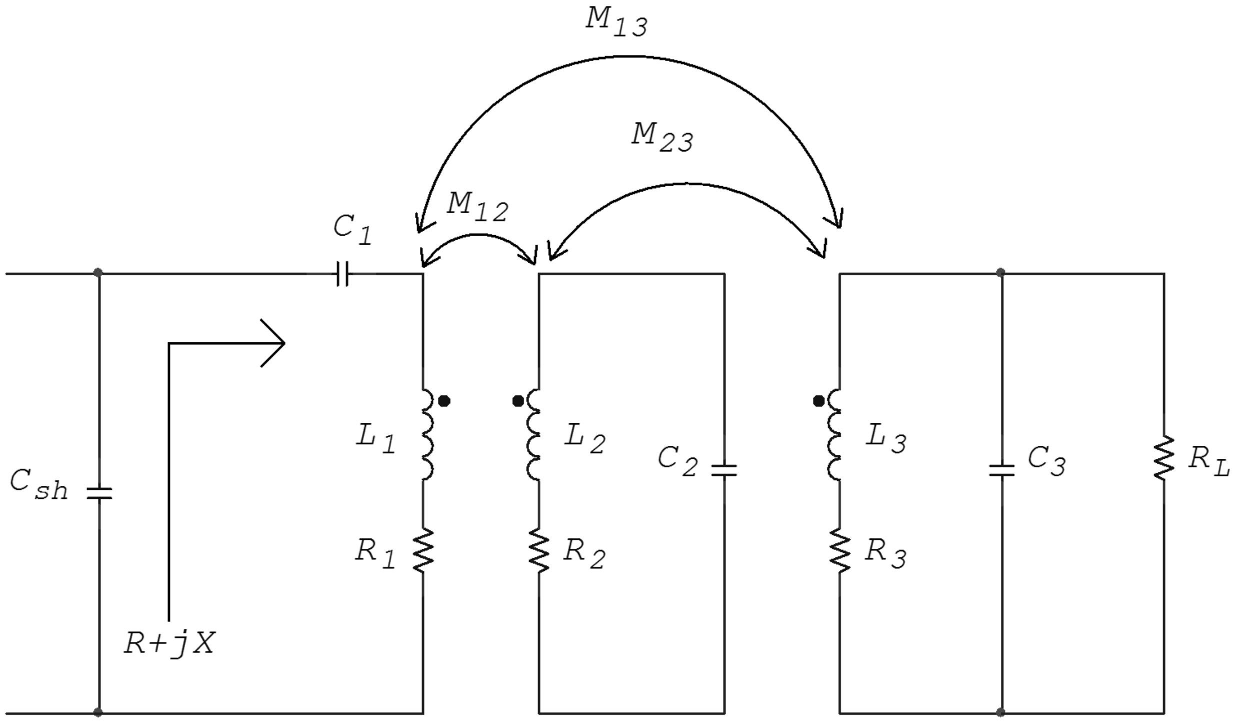

Fig 2. The inductive links forming the proposed system.

Table 1. The calculated system parameters for d_{12}=d$_{23}$=0.5m

Mutual Inductances	Coupling Coefficients	Inductances	AC Resistances
M_{12}= 0.066µH	K_{12}=0.011	L_1=6µH	R_1=0.26Ω
M_{23}=0.066µH	K_{23}=0.011	L_2=6µH	R_2=0.26Ω
M_{13}= 0.0096µH	K_{13}=0.0016	L_3=6µH	R_3=0.26Ω

L_1 and C_1 resonate at a frequency slightly less than f_0 and their equivalent impedance at the resonance frequency f_0 is $R+jX$, where R and X are defined by [17, 20]

$$R \approx R_1 + \frac{(\omega_0 M_{12})^2}{R_2 + \frac{(\omega_0 M_{23})^2}{R_3 + R_L}} \tag{7}$$

$$X = 1.152R = \omega_0 L_1 - \frac{1}{\omega_0 C_1} \tag{8}$$

Since the frequency of the proposed system is 5 MHz, then R and X are calculated as 17.16Ω and 13.12Ω, respectively. According to Equation (8), C_1 is calculated as 0.18135nF. C_{SH} is determined by [20]

$$C_{SH} = \frac{0.1936}{\omega_0 R} = 0.47nF \tag{9}$$

The rest components of the composite inductive shown in Fig 2 are C_2, C_3, and R_L. To achieve resonance conditions, $C_2 = C_3$ = 0.16873355nF.

Using the circuit parameters calculated above, the proposed system is design on PSpice/ Orcad16.6 as shown in Fig 3. The power amplifier of the proposed system is a class-E power amplifier driven by two n-channel MOSFET of the type 2N7000.

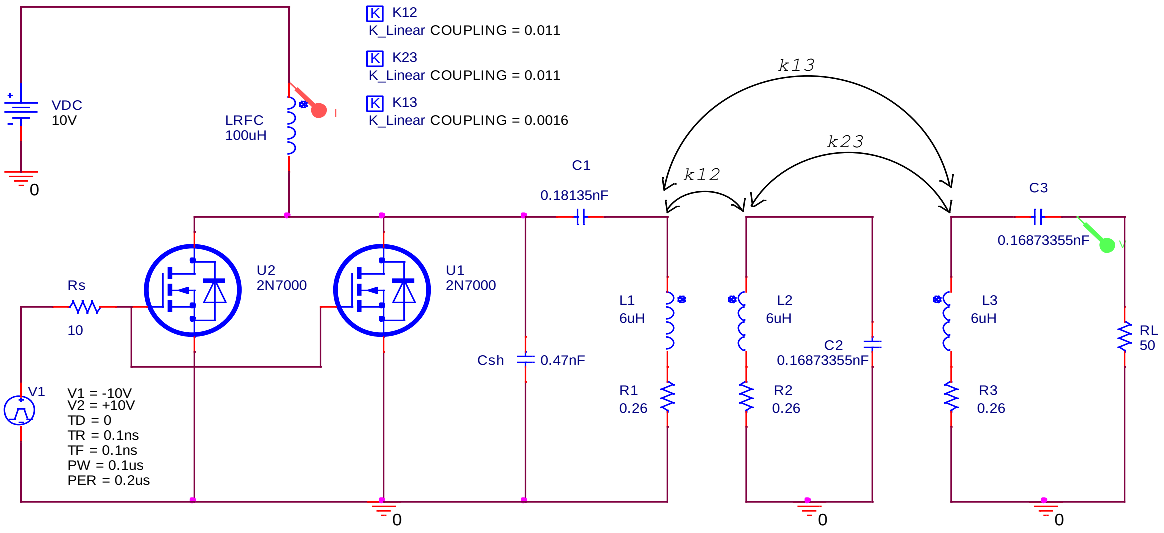

Fig 3. PSpice circuit diagram of the proposed system.

III. RESULTS AND DISCUSSION

The circuit of Fig 3 was tested on PSpice for investigating its performance without and with the existence of resonator coil. This means that, two WPT systems are considered here. The function of the proposed systems are energize a load node of 50Ω located at a distance of one meter from the transmitting coil. Simulation results are obtained in such a manner that they show the impact of inserting a resonator coil between transmitting and receiving coils. The results cover the AC voltage (V_T) across the transmitting coil, the AC voltage (V_{RS}) across the transmitting coil, the received AC voltage (V_0) across the load resistance, and the DC supply current (I_{DC}), which is the DC supply current supplied by the system supply voltage (V_{DC}=10V) and flowing through the radio frequency choke (L_{RFC}).

III.I System Results without Resonator

The results in this section concern the condition in which the proposed power transfer system has no resonator, which in turn means that the resonator coil does not exist in the circuit of Fig 3 (i.e. $k_{12}=k_{23}=0$). Fig 4 shows the AC voltage (V_T) across the transmitting coil. The figure shows an AC voltage of amplitude of 289V. Fig 5 shows the received AC voltage (V_0) across the 50Ω load resistance and the DC supply current (I_{DC}) of 0.423V and 86mA, respectively.

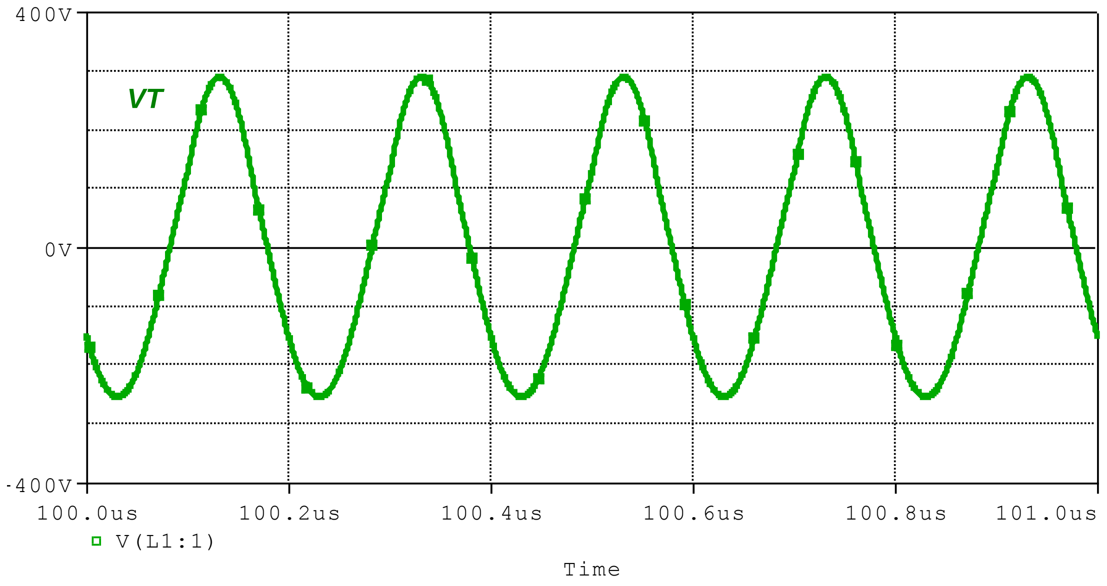

Fig 4. The AC transmitted voltage of the proposed system without resonator.

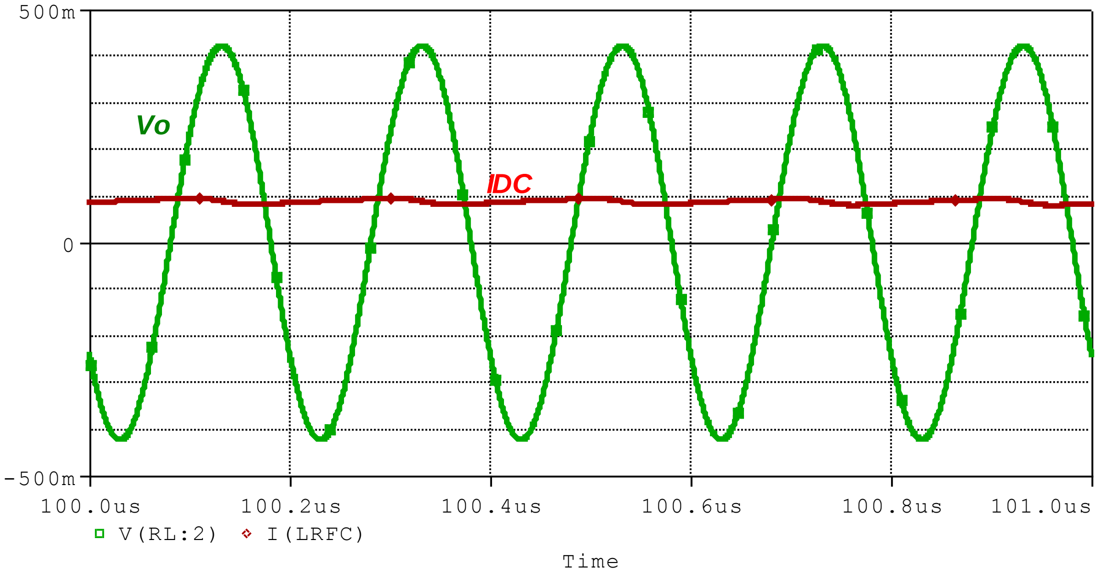

Fig 5. The AC received voltage and the DC supply current of the proposed system without resonator.

The transmitter input power or DC input power P_{DC} can be calculated by

$$P_{DC} = I_{DC}V_{DC} = 0.086A \times 10V = 0.86W \qquad (10)$$

The received AC power P_0 can be calculated by

$$P_0 = \frac{(V_{0P})^2}{2R_L} = \frac{(0.423V)^2}{2\times 50\Omega} = 1.79mW \qquad (11)$$

Where, V_{0P} represents the peak value of V_0. The percentage system efficiency $\eta\%$ can be determined by

$$\eta\% = \frac{P_0}{P_{DC}} \times 100\% = \frac{1.79mW}{0.86W=0.} \times 100\% = 0.21\% \qquad (12)$$

The above efficiency represents the percentage power transmission efficiency of a 5 MHz WPT system energizing a 50Ω resistive load located at a distance of 1m from its transmitter.

III.II System Results with Resonator

The results in this section concern the condition in which the proposed power transfer system has a resonator coil located at mid-distance between transmitting and receiving coils. Fig 6 shows the AC voltage (V_T) across the transmitting coil and the AC voltage V_{RS} across the resonator coil. The figure shows amplitudes of 154V and 820.4V for V_T and V_{RS}, respectively. Fig 7 shows the received AC voltage (V_0) across the 50Ω load resistance and the DC supply current (I_{DC}) of 9.1V and 0.346A, respectively.

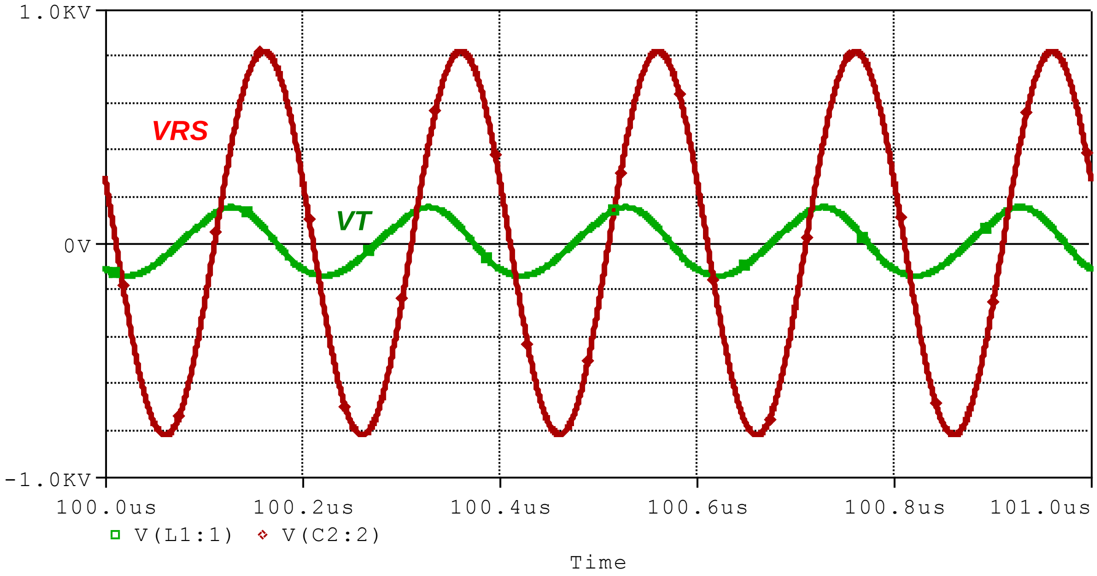

Fig 6. The AC transmitted voltage and the resonator voltage of the proposed system with resonator.

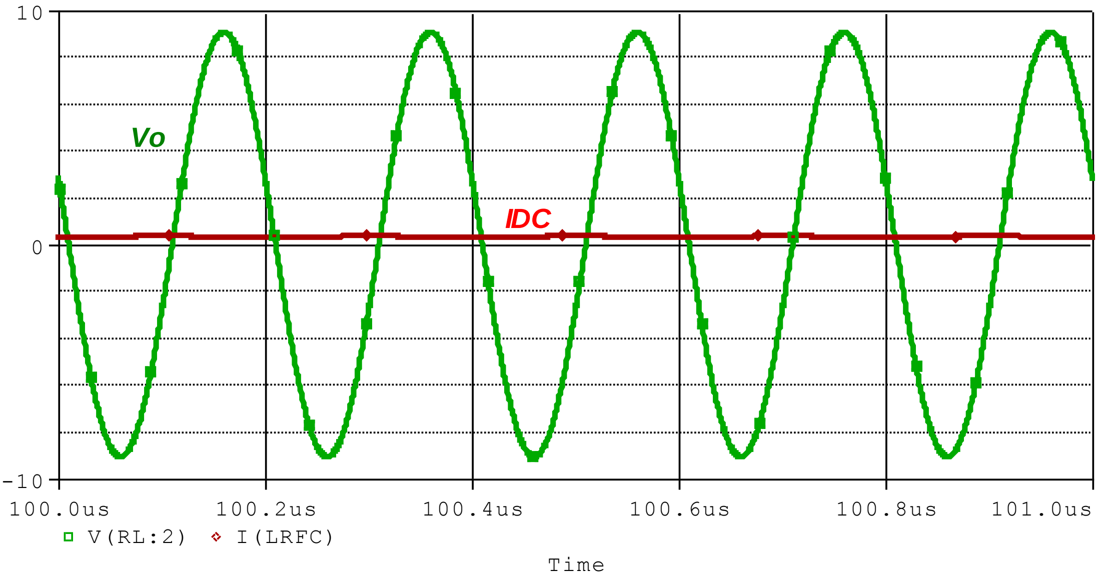

Fig 7. The AC received voltage and the DC supply current of the proposed system with resonator.

Using (10), (11), and (12), the transmitter input power P_{DC}, output power P_0, and percentage efficiency $\eta\%$ are calculated as P_{DC}= 3.46W, P_0= 0.8281W, and $\eta\%$=24%.

The system percentage efficiency with resonator is 24/0.21=114.3 times that without using resonator. This means that inserting a similar resonator coil at mid-distance between two similar sending and receiving coils enhances the system efficiency by 114.3 times that of a similar system having no resonator.

IV. CONCLUSION

In this work, different WPT systems are reviewed. It is proved here that the power transmission efficiency can be strongly enhanced through inserting a third coil known as a resonator between transmitting and receiving coils. To show the impact of this work, two 5 MHz WPT systems are designed and tested in this work. Both systems are required to energize a 50Ω resistive load located at 1m from the power transmitting coil. The first system has no resonator coil, while the second system is equipped with a mid-distance resonator coil. It is verified that the power transmission efficiency of the second system is enhanced by 114.3 times that of the WPT system having no resonator.

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