Reduction of Output Power Pulsations for Electric Vehicles by Changing Distances between Transmitter Coils

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Abstract — **Researchers are showing significant interest on wireless charging of electric vehicles (EVs) and this concept is becoming popular and growing very fast. Using wireless charging technique, it is possible to considerably decrease fossil fuel consumption and reduce pollution created by vehicles in one hand and reduce electric cord hazards in EV charging on the other hand. EV wireless charging systems can be divided into two groups: Stationary Wireless Charging (SWC) and Dynamic Wireless Charging (DWC). However, DWC has more advantages as compared to SWC, in terms of charging time and reducing battery size. Despite of the fact that DWC has more positive sides, there are issues with efficiency of the system since the vehicle charges once it is in motion. One of the possible ways to solve this problem is reduction of power pulsations while dynamically charging. This study discusses and analyzes the effect of distance between adjacent transmitter coils on DWC system output. Mathematical modeling for multi-channel DWC is carried out and simulation is performed with different distances between transmitter coils and the results are discussed in detail. A possible solution to reduce pulsation is provided and future work is discussed**

Keywords— Adjacent Transmitter Coils; Dynamic Wireless Chargin; Electric Vehicles; Mutual Inductance; Pulsations.

I. INTRODUCTION

Nowadays, eco-friendly energy is one of the most discussed topics around the World. Significant amount of pollution produced by cars can lead to dramatic decrease of the environment conditions. Moreover, the issue with depletion of fossil fuels forced and encouraged people to think about alternatives to the conventional vehicles to reduce the consumption [1]-[7].Therefore, different electric vehicles, namely Battery Electric Vehicles (BEV), Hybrid Electric Vehicles (HEV), Fuel Cell Electric Vehicles (FCEV) and Fuel Cell Hybrid Vehicles (FCHV), came to the picture to solve the problem [1],[8],[9]. Some of these vehicles use electric as well as combustion engines and have plug-in battery system. Despite the fact that the pollution problem was mitigated by this solution, hybrid vehicles were not used widely due to main disadvantages of the battery such as size, weight, price and long charging time. So, alternatively wireless charging technique was introduced. Wireless charging technique or Wireless Power Transfer (WPT) is transmission of electrical power from source to load without physical connector [8]. Generally, wireless power transfer can be divided into two classes: static and dynamic. Both of the methods transfer power without any wire, which ensures safety, isolation of power and reliability [10],[11].The main difference between them is that in static wireless charging power is transmitted by stationary coils, whereas in dynamic wireless charging the receiver is in motion[1],[12]-[15]. In addition, in static wireless power transfer, vehicle can be charged only on specific charging station and the time when vehicle is active is comparably short. Currently, the main constraints are related with expensive battery, charging station location and long charging time, therefore new method, namely roadway powered dynamic wireless charging of electric vehicles is proposed. The main advantage of these roadway powered electric vehicles is that it can be charged while the vehicle is in motion, which means that there is no waiting time, longer travelling distance and smaller size of battery[16]. The idea of the method is about transferring electrical energy between two coils, namely inductive coupling [17],[18]. Transfer of the power occurs by utilization of magnetic fields created by transmitter side. Primary coil starts to produce magnetic fields across secondary coil and then, current is induced across the secondary coil due to the magnetic power. Thus, having magnetic field between transmitter and receiver coils, the electric vehicle can be charged [19]. However, the main limitation of the system of dynamic wireless charging is the efficiency of power transfer and this occurs because the charging procedure happens in dynamic circumstances. In other words, there is always constant lateral misalignment between coils which leads to decrease in power efficiency [1]-[5]. These misalignments or pulsations are created because the vehicle passes roadway coils and charging occurs not smoothly which consequently decrease power efficiency and degrade battery service life. Therefore, one of the solutions to increase the efficiency and to smooth charging process of the dynamic wireless charging is to decrease the distance between adjacent roadway coils [20]. The aim of this study is to analyze and examine charging of the system for several distances between adjacent transmitters, compare simulation outputs and prove that proposed method increases efficiency of the overall system.

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II. Method for Measuring Inductance

A. Determination of mutual and self inductances

According to [21], self and mutual inductances of the coils depend only on geometric parameters of windings. Figure 1 illustrates the winding model of two coils (A and B) with air core

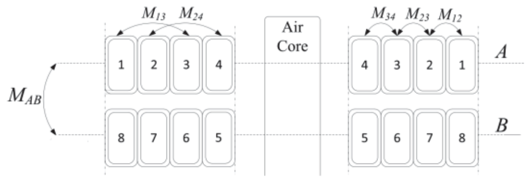


Fig. 1. Winding model of two coils with air core, taken from [21]

where M_{AB} is the mutual inductance of disk A and B, M_{12} is the turn to turn mutual inductance of turns 1 and 2.

Taking into consideration Fig. 1, the inductance matrix of the disk A and mutual inductance matrix of disks A and B are obtained as:

$$L_A = \begin{pmatrix} L_1 & M_{12} & M_{13} & M_{14} \\ M_{21} & L_2 & M_{23} & M_{24} \\ M_{31} & M_{32} & L_3 & M_{34} \\ M_{41} & M_{42} & M_{43} & L_4 \end{pmatrix}$$
$$M_{AB} = \begin{pmatrix} M_{15} & M_{16} & M_{17} & M_{18} \\ M_{25} & M_{26} & M_{27} & M_{28} \\ M_{35} & M_{36} & M_{37} & M_{38} \\ M_{45} & M_{46} & M_{47} & M_{48} \end{pmatrix} \quad (1)$$

where L_1 represents turn inductance.

The total self-inductance of the disc is found via integration of all the mutual and self-inductances of each turn. Thus,

$$L_{A\text{-}disc} = L_1 + L_2 + L_3 + L_4 + 2\begin{pmatrix} M_{12} + M_{13} + M_{23} \\ +M_{14} + M_{24} + M_{34} \end{pmatrix} \quad (2)$$

$$M_{A\text{-}disc} = 2\left(M_{12} + M_{13} + M_{23} + M_{14} + M_{24} + M_{34}\right) \quad (3)$$

Equations (2), (3) can be extended for different number of turns and discs [21].

B. Case with one transmitter and one receiver

It is important to understand the concept of determining the mutual inductance in different systems. To find mutual inductance, it is required to estimate the self-inductance of the coils. Figure 2 shows two coupled coils which are connected in series and have self-inductances, namely L_1 and L_2. It is considered that the magnetic fields of the inductors are in the same direction.

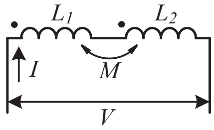


Fig. 2. Series connected coils with the same magnetic field direction

Considering that the current flows to the system, the equation for voltage becomes:

$$V = V_1 + V_{M,1} + V_2 + V_{M,2} \quad (4)$$

where $V_{M,1}$ and $V_{M,2}$ are the voltages created by mutual inductance M between two coils, and L_1 and L_2 induce voltage which are V_1 and V_2. As it was mentioned, the magnetic fields are in the same direction, therefore all voltages have positive sign. In addition, induced voltages $V_{M,1}$ and $V_{M,2}$ should be equal due to series connection of inductors. Applying Lenz's law, the voltage becomes:

$$V = -L_1\frac{dI}{dt} - M\frac{dI}{dt} - L_2\frac{dI}{dt} - M\frac{dI}{dt} = -(L_1 + L_2 + 2M)\frac{dI}{dt} \quad (5)$$

According to (5), the self-inductance of the system is:

$$L = L_1 + L_2 + 2M \quad (6)$$

By rearranging (6), the mutual inductance can be estimated:

$$M = \left(L - (L_1 + L_2)\right)/2 \quad (7)$$

Also, the mutual inductance can be determined if the inductors have opposite magnetic fields.

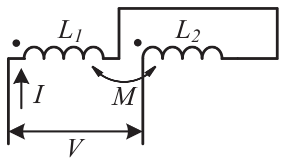


Fig. 3. Series connected coils with opposing magnetic field direction

According to Fig. 3:

$$V = V_1 - V_{M,1} + V_2 - V_{M,2} \quad (8)$$
$$= -L_1\frac{dI}{dt} + M\frac{dI}{dt} - L_2\frac{dI}{dt} + M\frac{dI}{dt} = -(L_1 + L_2 - 2M)\frac{dI}{dt}$$

From (8) self-inductance of the system with opposing magnetic fields becomes:

$$L = L_1 + L_2 - 2M \quad (9)$$

Mutual inductance from (9) can be rearranged as:

$$M = \left((L_1 + L_2) - L\right)/2 \quad (10)$$

C. Case with several transmitters and one receiver

In this part system with four transmitters and one receiver will be considered. From Fig. 4, it is clearly seen that there are four mutual inductances in the system ($M_{15}, M_{25}, M_{35}, M_{45}$).

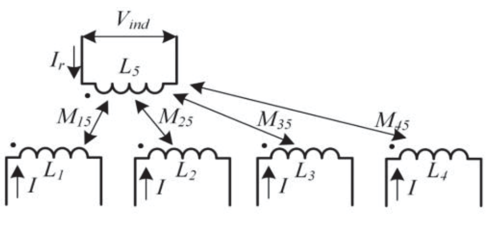


Fig. 4. System with four transmitters and one receiver

Induced voltage in the receiver side can be obtained by:

$$V_{ind} = -L_5 \frac{dI_r}{dt} - (M_{15} + M_{25} + M_{35} + M_{45}) \frac{dI}{dt} \quad (11)$$

According to (11), the equation for induced voltage consists of self-induced EMF and mutual coupling of transmitters with receiver. Therefore, from this it can be concluded that the total mutual inductance in parallel transmitters system is the sum of separate mutual inductances [21]-[24].

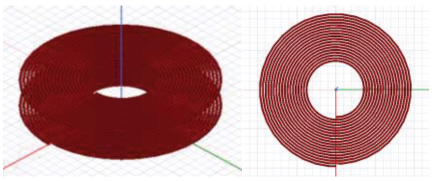
D. Simulation of mutual inductance for one transmitter and one receiver

The coils are designed from copper to be circular shaped and with self-inductance of 86.8 µH. From Table I the parameters for transmitter and receiver coils can be seen.

TABLE I. TRANSMITTER AND RECEIVER COIL PARAMETERS

Parameter	Transmitter and receiver coils
Number of turns	18
Inner diameter	140 mm
Conductor diameter	4 mm
Turn spacing	3 mm
Outer diameter	400 mm

Simulation was performed in ANSYS Maxwell software. The distance between transmitter and receiver was taken as 6 cm and coils were excited with 6A current source. Fig. 5 illustrates 3D and top view of simulated coils:



(a) (b)

Fig. 5. ANSYS Simulation of coils in perfect alignment: (a) 3D view, (b) top view.

The variable mutual inductance was obtained by considering different positions of receiver coil. In other words, the receiver coil was moved along 11 positions (50cm, 40cm, 30cm, 20cm, 10cm, 0cm, 10cm, 20cm, 30cm,40cm, 50cm between centers of transmitter and receiver), strictly parallel to transmitter coils. It means that the receiver coil moved above transmitter coil's center for 100 cm only along X-axis. Table II and Fig.6 show the simulation results which were obtained from simulation study.

TABLE II. SIMULATION RESULTS OF MUTUAL INDUCTANCE FOR DIFFERENT RECEIVER POSITIONS

Position #	Mutual inductance (µH)	Position #	Mutual inductance (µH)
1	-1.11	7	27.9
2	-2.23	8	6.63
3	-2.64	9	-2.63
4	6.62	10	-2.21
5	27.9	11	-1.12
6	41.1		

E. Simulation of mutual inductance for several transmitters and one receiver

It should be stated that the radius of coils simulated software was taken to be 20cm. To analyze the behavior of the mutual inductance, the distances between transmitters were 10cm, 0cm, and 10cm overlap. From Fig. 8 it is seen that the minimum mutual inductance between transmitter and receiver occurs when the receiver passes the gap between transmitters. Generally, due to this gap overall behavior of mutual inductance (red line) has strong fluctuations.

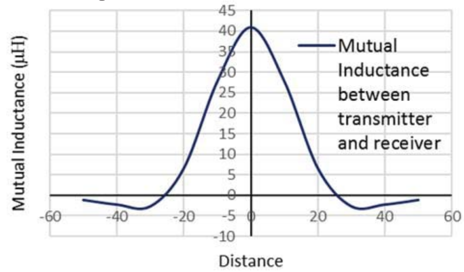
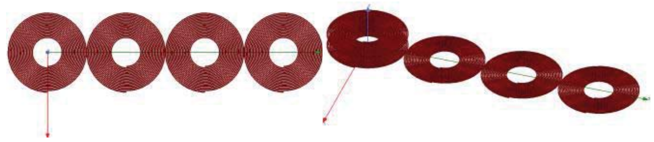


Fig. 6. ANSYS Simulation of mutual inductances for different positions of receiver coil



(a) (b)

Fig. 7. ANSYS Simulation of coils with distance between transmitters 0 cm: (a) top view, (b) 3D view

If the gap between transmitters is decreased, the mutual inductance tends to increase and becomes stable. For the case with 0cm gap between transmitters (Fig. 9), the mutual inductance increased from 3µH to 13µH. Moreover, if the transmitters overlap for 10cm, the fluctuation significantly decreases, which is shown on Fig. 10. In addition, the mutual inductance is higher at first and last coils. This happens due to less negative coupling at beginning and end of receiver way. The simulation has shown that the smaller the distance between transmitters, the higher mutual inductance between coils. By applying this knowledge, the problem with power pulsations of the system can be mitigated.

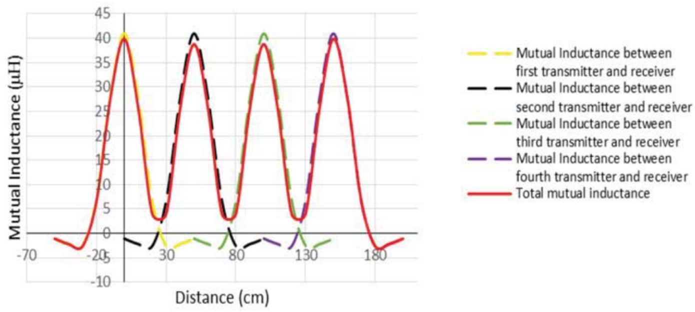


Fig. 8. Mutual inductance between transmitter and receiver coils for 10cm gap between transmitters

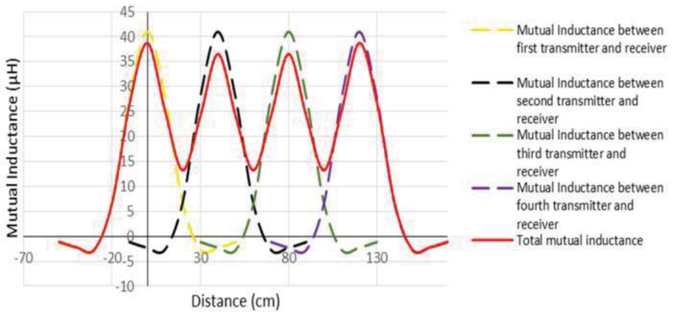


Fig. 9. Mutual inductance between transmitter and receiver coils for 0cm gap between transmitters

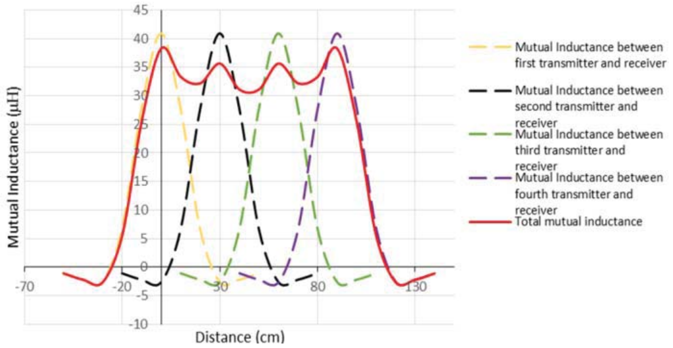


Fig. 10. Mutual inductance between transmitter and receiver coils for 10cm overlap between transmitters

III. DYNAMIC WIRELESS CHARGING SYSTEM DESIGN

A. System Description of Dynamic Wireless Charging

The system of Dynamic Wireless Charging, which is illustrated on Fig. 11, consists of several parts, namely inverter, compensation circuits, one receiver coil, four transmitter coils and switches.

Inverter – converts DC voltage to AC signal. The main idea of using AC signal is higher efficiency in coupling.

Switches – the purpose of using switches is minimizing losses and therefore increasing efficiency by turning on and off only needed transmitters.

Compensation circuit – this component of the system is aimed to cut out unwanted frequencies and increase resonant frequency signal. In addition, compensation circuit decreases the reactive power in the system, which significantly increase the efficiency. It should be noticed that the transmitter side compensation circuit is LCC type, however at receiver side the compensation circuit consists of only capacitor in series.

Transmitter coils – current flowing in the transmitter coils induce the magnetic field.

Receiver coils – receiver side coils are induced by transmitter side to create electromotive force.

The system works at 20 kHz frequency and 18 V DC source. Other parameters are shown on Table III.

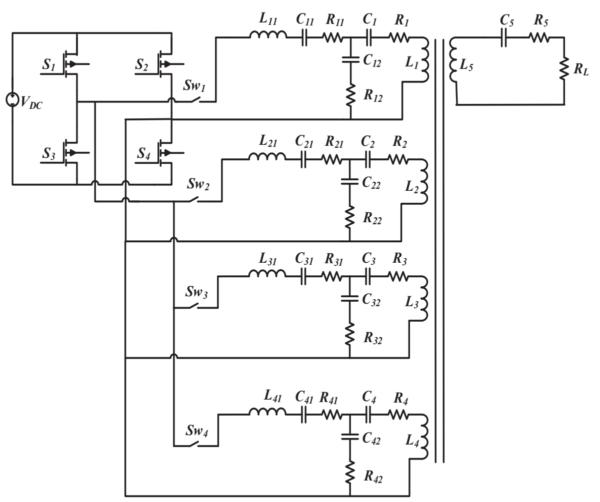


Fig. 11. Overall system circuit of Dynamic Wireless Charging

TABLE III. CIRCUIT PARAMETER VALUES

Parameter	Value
L_1, L_2, L_3, L_4, L_5	90 µH
R_1, R_2, R_3, R_4	40 mΩ
C_1, C_2, C_3, C_4, C_5	690 nF
$L_{11}, L_{21}, L_{31}, L_{41}$	11 µH
$R_{11}, R_{21}, R_{31}, R_{41}, R_{12}, R_{22}, R_{32}, R_{42}$	10 mΩ
$C_{12}, C_{22}, C_{32}, C_{42}$	6 µF
M_{12}, M_{23}, M_{34}	1 µH
R_L	15 Ω

B. Mathematical Model

To provide analytical model of the system, mesh current analysis was applied to circuit which is shown on Fig. 11. Following matrix is the result of the overall system:

$$\begin{pmatrix} Z_{11} & Z_{12} & 0 & 0 & Z_{15} & Z_{16} & 0 & 0 & 0 \\ Z_{21} & Z_{22} & Z_{23} & 0 & Z_{25} & 0 & Z_{27} & 0 & 0 \\ 0 & Z_{32} & Z_{33} & Z_{34} & Z_{35} & 0 & 0 & Z_{38} & 0 \\ 0 & 0 & Z_{43} & Z_{44} & Z_{45} & 0 & 0 & 0 & Z_{49} \\ Z_{51} & Z_{52} & Z_{53} & Z_{54} & Z_{55} & 0 & 0 & 0 & 0 \\ Z_{61} & 0 & 0 & 0 & 0 & Z_{66} & 0 & 0 & 0 \\ 0 & Z_{72} & 0 & 0 & 0 & 0 & Z_{77} & 0 & 0 \\ 0 & 0 & Z_{83} & 0 & 0 & 0 & 0 & Z_{88} & 0 \\ 0 & 0 & 0 & Z_{12} & 0 & 0 & 0 & 0 & Z_{99} \end{pmatrix} \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_{11} \\ I_{21} \\ I_{31} \\ I_{41} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ U_{11} \\ U_{21} \\ U_{31} \\ U_{41} \end{pmatrix} \quad (12)$$

where I_1, I_2, I_3, I_4 are transmitter coil currents, I_5 is receiver coil current, I_{11}, I_{21}, I_{31}, I_{41} resonator input currents, U_{11}, U_{21}, U_{31}, U_{41} are resonator input voltages. Equation (13) shows the impedances of matrix which are estimated according to Fig. 11.

$$\begin{aligned} & Z_{11} = R_1 + R_{12} + jwL_1 + 1/(jwC_1) + 1/(jwC_{12}) \\ & Z_{22} = R_2 + R_{22} + jwL_2 + 1/(jwC_2) + 1/(jwC_{22}) \\ & Z_{33} = R_3 + R_{32} + jwL_3 + 1/(jwC_3) + 1/(jwC_{32}) \\ & Z_{44} = R_4 + R_{42} + jwL_3 + 1/(jwC_4) + 1/(jwC_{42}) \\ & Z_{55} = R_L + R_5 + jwL_5 + 1/(jwC_5) \\ & Z_{66} = R_{11} + R_{12} + jwL_{11} + 1/(jwC_{11}) + 1/(jwC_{12}) \\ & Z_{77} = R_{21} + R_{22} + jwL_{21} + 1/(jwC_{21}) + 1/(jwC_{22}) \\ & Z_{88} = R_{31} + R_{32} + jwL_{31} + 1/(jwC_{31}) + 1/(jwC_{32}) \\ & Z_{99} = R_{41} + R_{42} + jwL_{41} + 1/(jwC_{41}) + 1/(jwC_{42}) \\ & Z_{12} = Z_{21} = jwM_{12}; Z_{23} = Z_{32} = jwM_{23}; Z_{34} = Z_{43} = jwM_{34} \\ & Z_{15} = Z_{51} = -jwM_{15}; Z_{25} = Z_{52} = -jwM_{25}; \\ & Z_{35} = Z_{53} = -jwM_{35}; Z_{45} = Z_{54} = -jwM_{45}; \\ & Z_{16} = Z_{61} = -(R_{12} + 1/(jwC_{12})); \\ & Z_{27} = Z_{72} = -(R_{22} + 1/(jwC_{22})); \\ & Z_{38} = Z_{83} = -(R_{32} + 1/(jwC_{32})); \\ & Z_{49} = Z_{94} = -(R_{42} + 1/(jwC_{42})); \end{aligned} \quad (13)$$

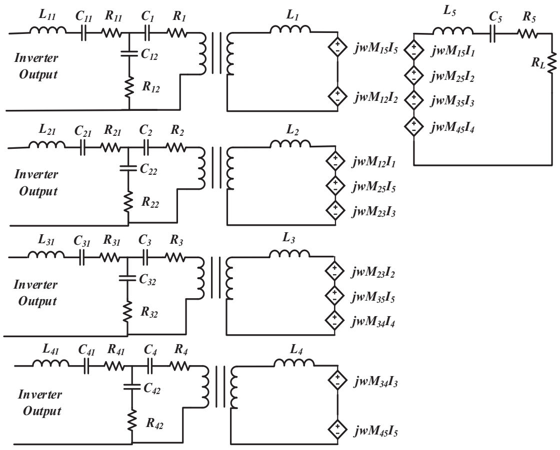


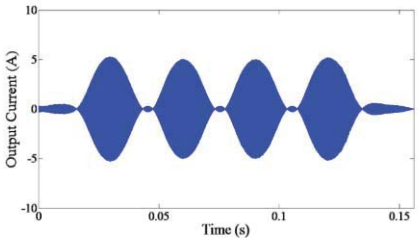
Fig. 12. Mutual couplings of the system simulated in Simulink

C. Simulation of Dynamic Wireless Charging System

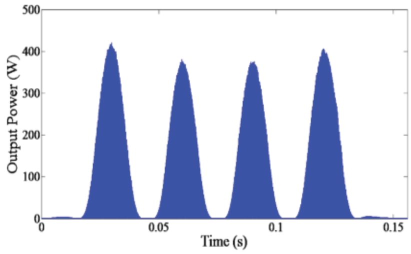
Using simulation study the circuit illustrated on Fig. 12 was created. Mutual couplings between coils of the system are modeled as controlled voltage sources. Each of the transmitter coils has mutual coupling with neighboring transmitter coil and receiver coil [25].

D. Simulation Results of Dynamic Wireless Charging System Units

In this study, three cases for adjacent transmitter coil distances were considered, when there is 10cm gap, 0 cm gap and 10cm overlap between transmitter coils. From Figures 13, 14 and 15 it is clearly seen the behavior of power pulsations of the system and it can be concluded that power pulsations can be decreased by reducing distance between transmitter coils. Consequently, the overall efficiency of the system increases with smoothing of pulsations.

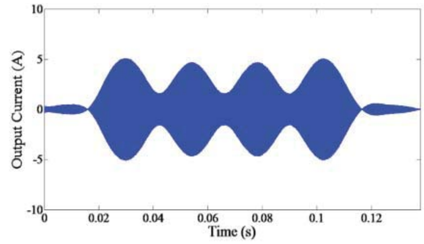


(a)



(b)

Fig. 13. Output Current (a) and Output Power (b) of the system with 10 cm gap between transmitter coils



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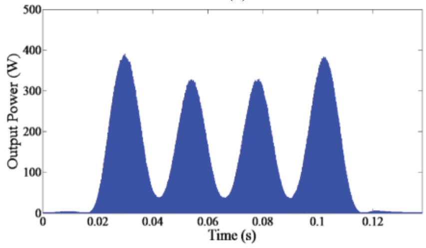
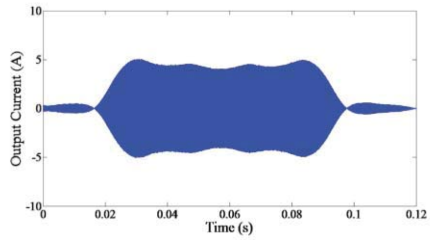


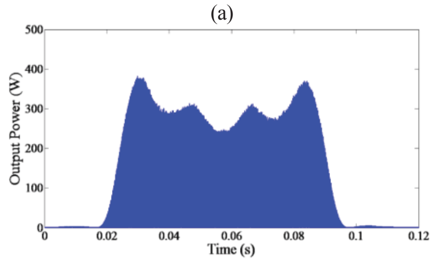
(b)

Fig. 14. Output Current (a) and Output Power (b) of the system with 0 cm gap between transmitter coils

The system was also emulated in simulator to find out the safe distance from coils at which magnetic flux will not have effect on human body. The coils were placed in box with parameters of 500mm, 1700mm, 200mm X-size, Y-size, Z-size respectively. According to the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [26], the possible magnetic flux in range of 3kHz-10MHz is 27µT at distance of maximum 20cm. In other words, if the magnetic flux exceeds 27µT at distance larger than 20cm from the source, it can be assumed as harmful for human health. From Fig. 16, it is clearly seen that the value of magnetic flux is less than 27µT even in 20cm distance from excited coils.



(a)



(b)

Fig. 15. Output Current (a) and Output Power (b) of the system with 10 cm overlap between transmitter coils

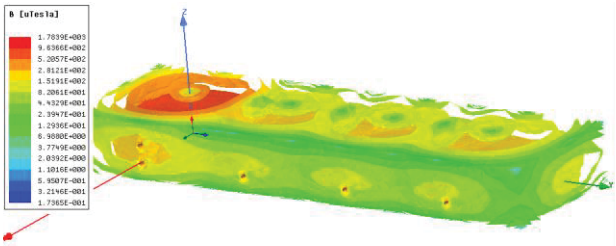


Fig. 16. Transmitter and receiver coils with magnetic flux

IV. CONCLUSION

The effect of distance of adjacent transmitter coils on output power pulsations was discussed. It was shown that the output power pulsations become less and smoother when the distance between transmitters decrease. This was discussed through simulation study. Analytical model of the dynamic wireless charging was also discussed. In addition, it must be noticed that the mutual inductance between coils plays significant role in mitigating the problem with output power pulsations, in other words, by decreasing the mutual inductance pulsations, the power pulsations can be decreased. However, closing the transmitter coils may not become economical. Hence, a combination of adjusting transmitter coils distance and rectangular shape coils may be recommended. It is worth noting that, rectangular coils have less performance in DWC as compared to circular coils which are very effective in terms of mutual coupling. Furthermore, this study discussed the effect of magnetic flux of simulated coils on human body and using simulation study it was shown that magnetic flux is in the range of permitted value by guidelines. For future work, the circuit of dynamic wireless charging system can be developed in more comprehensive way with rectifiers and other type of compensation circuits to reach higher efficiencies.

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