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Soft Switching in Closely Spaced Multi-Transmitter Wireless Power Transfer Systems

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***Abstract*—This paper presents a novel idea to enhance the switching of power electronic converters used for driving closely spaced multi-transmitter (MT) wireless power transfer (WPT) systems. Cross coupling amongst the transmitters is an undesirable phenomenon for power electronic converters as they induce an spurious voltage in the adjacent coils. Therefore, with the use of coupled inductors (CPIs) a new method to mitigate the effects of cross couplings is proposed. To study the effect of CPIs on soft switching, an MTWPT system consisting of three transmitters and one receiver is used as a case study. The system is mathematically analysed, numerically simulated, and experimentally tested, and the results validate the efficacy of the proposed approach.**

***Index Terms*—Cross Coupling, Dynamic Wireless Power Transfer Systems, LCC Compensators, Soft Switching, Wireless Power Transfer Systems, Zero Current Switching (ZCS).**

I. INTRODUCTION

Wireless power transfer (WPT) systems have been increasingly gaining attention in numerous applications. Some of the attractive features of these systems are flexibility of consumers position, absence of mechanical connectors to transfer the power, and safety of the receiver side in wet or dirty environments [1]–[3]. These advantages make WPT system to be an attractive option in medical applications, such as biomedical implants [4], consumer electronics devices [5], and automotive industries, as stationary and dynamic chargers for electric vehicles [2], [6].

To serve a better functionality, these systems, however, become more complicated with the use of advanced scientific and technological devices and techniques. For example, [7] proposes the idea of magnetic resonators to increase the distance between transmitters and receiver, this is done by adding repeater coils between transmitter and receiver. Zhong et al. [8] suggest to add additional repeaters to further extend and direct the path of WPT. In [3], DDQ coils are proposed to remove the power null in the transferred power (TP) profile. In addition, with the use of multi-parallel arrangement of LCC coils, the magnetic profile of the MTWPT system is expanded. In almost all these innovations, more WPT coils are added to the system, which along with the enhancement in operation, brings about some new issues.

The issue that is specifically focused in this paper is the undesirable effect of transmitter cross couplings on soft switching of the driving converters. This issue is mentioned in [9], in which a minimum distance between individually driven transmitters is found to avoid the occurrence of the phenomenon. This, however, results in a large TP fluctuations because the transmitters are not effectively close to each other.

Therefore, a simple method based on coupled inductors is proposed in this paper to compensate the undesirable effect of cross couplings amongst the transmitters on switching of the driving power electronic converter. To explain the proposed approach, an MTWPT system, consisting of three transmitters and one receiver, is considered as a case study, which is elaborated in section II. In section III, the operation of the system equipped with coupled inductors and driven by a four-legged converter is explained. Furthermore, this section explains the designing steps for a refined LCC compensator with the use of CPI. The simulated and experimental results are also provided in Section IV, followed by the conclusions in Section V.

II. THE FOUR-COIL MTWPT SYSTEM

As it is shown in Fig. 1, the system consists of three closely spaced transmitters and one receiver, also known as pickup. The pickup can move along x axis, from $-55cm$ to $55cm$, and as a result, the inductance profile of the system varies. Fig. 2 shows the variation of the inductances for transmitter and receiver self-inductances, transmitter-receiver mutual inductances (trans couplings), and transmitter-transmitter mutual inductances (cross couplings) that are obtained from experimental measurements.

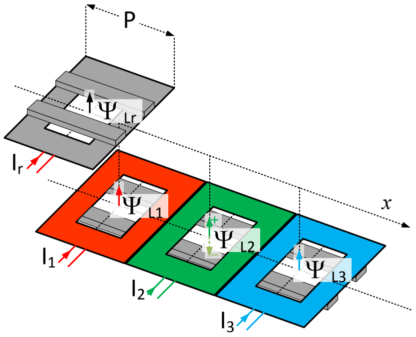


Fig. 1. Structure of the magnetic system.

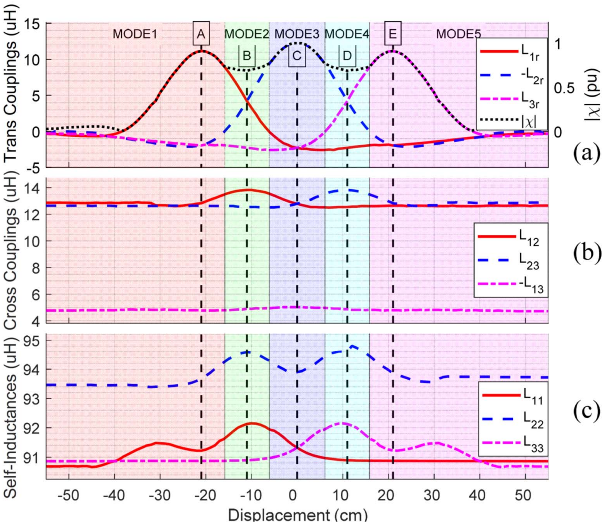


Fig. 2. Inductance profile of the MTWPT system for (a) transmitter and receiver self-inductances, (b) transmitter-receiver mutual inductances (trans couplings), and (c) transmitter-transmitter mutual inductances (cross couplings).

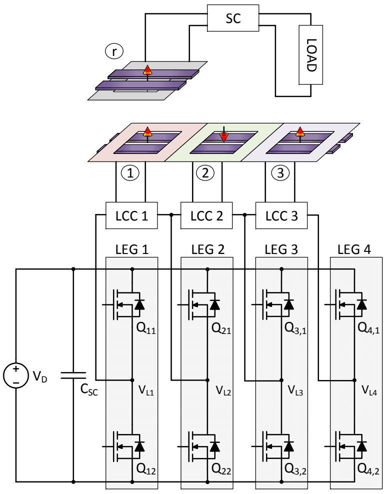


Fig. 3. 4LC to drive the three transmitters of the four-coil MTWPT system.

Fig. 2 also shows that trans couplings vary depending on the position of the pickup. They are at their highest value when the pickup is aligned with the corresponding transmitter, and they start to decrease when the pickup is moving away from the aligned position. Therefore, by exciting one or more transmitter(s) at the same time, pickup can receive a stable TP profile. According to the inductance profiles shown in Fig. 2, five modes of operation are defined for the MTWPT system to obtain the highest possible TP. In mode “1”, only transmitter “1” is excited. Mode “2” is associated with the co-operation of both transmitters “1” and “2”. In mode “3”, transmitter “2” is responsible for WPT. Similar to mode “2”, in mode “4”, transmitters “2” and “3” transfer the power. And finally, in mode “5”, transmitter “3” is the only coil which transfers the power.

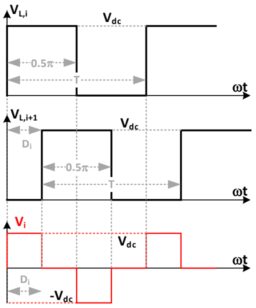


Fig. 4. Leg-to-ground and leg-to-leg voltages of two adjacent legs.

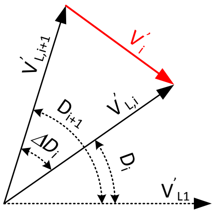


Fig. 5. Voltage phasors of leg-to-ground $V'_{\mathrm{L}i}$ and leg-to-leg V_i fundamentals of the adjacent legs in a 4LC ($V'_{\mathrm{L}i}$ is the fundamental component of $V_{\mathrm{L}i}$).

III. REFINED LCC COMPENSATOR

The proposed method of compensation can be used for any type of power converters, such as H-Bridge, N-Legged Converter, etc. In this paper, a four-legged converter (4LC) is chosen to drive the WPT system, as shown in Fig. 3 [10]. The required modulation technique and resultant phasors of the output voltage are shown in Fig. 4 and Fig. 5 respectively.

In Fig. 6, how CPIs are used in the compensators to form a refined LCC network is shown. CPIs are consisting of two coupled inductors, which are tuned to have a mutual inductance close but in an opposite direction of the connected coils cross coupling. Therefore, connecting each side of these coils in series with the cross-coupled coils, CPIs can compensate the cross couplings. The integration of an LCC network with CPIs is termed as refined LCC compensator. Fig. 7 shows the equivalent circuit diagram of the refined LCC network compensating a transmitter of the MTWPT system.

The governing equation for the current of the LCC primary loop can be obtained from (1). In this equation, $C_{\mathrm{S},i}$, $C_{\mathrm{P},i}$, and $L_{\mathrm{S},i}$ are series capacitor, parallel capacitor, and series inductor of the LCC compensator respectively. L_{ij} and L_{ii} are the cross coupling and self-inductance of the transmitters respectively, $L_{\mathrm{T},ij}$ and $L_{\mathrm{T},ii}$ are the cross coupling and self-inductance of the CPIs respectively, Z_{L} is the compensated load at the pickup side, and V_i is the fundamental leg-to-leg voltage of the converter. The current of the transmitter is $I_i = -\mathrm{j}\omega C_{\mathrm{P}i} V_i$.

To meet soft switching requirements for fundamental harmonics of voltage (V_i) and current (I_i) seen from the converter terminals, V_i and I_i must be in the same phase. Therefore, the quadrature components of cross couplings are not desirable and can disrupt the soft switching. Owing to the small variations of cross couplings by displacement of the pickup, as shown in Fig. 2(b), cross couplings can be compensated by the

$$I_{\mathrm{LS},i} = \underbrace{\left(C_{\mathrm{P},i}L_{ii}\omega^2 - 1 - \frac{C_{\mathrm{P},i}}{C_{\mathrm{S},i}}\right)\left(\mathrm{j}\,\overbrace{\omega C_{\mathrm{P},i}V_i}^{|I_i|}\right)}_{\text{Quadrature term (Independent)}} + \underbrace{\left(C_{\mathrm{P},i}\omega^2\sum_{k=1}^{n-2}L_{\mathrm{T},ii}\right)\left(\mathrm{j}\,\overbrace{\omega C_{\mathrm{P},i}V_i}^{|I_i|}\right)}_{\text{Quadrature term (CPI self-inductance)}} + \underbrace{C_{\mathrm{P},i}\omega^2\sum_{k=1\neq i}^{n-1}L_{ki}\left(\mathrm{j}\,\overbrace{\omega C_{\mathrm{P},k}V_k}^{|I_k|}\right)}_{\text{Quadrature term (Cross coupling)}}$$

$$\underbrace{-\,C_{\mathrm{P},i}\omega^2\sum_{k=1\neq i}^{n-1}L_{\mathrm{T},ki}\left(\mathrm{j}\,\overbrace{\omega C_{\mathrm{P},k}V_k}^{|I_k|}\right)}_{\text{Quadrature term (CPI compensation)}} + \underbrace{\left(\frac{C_{\mathrm{P},i}}{Z_{\mathrm{L}}}L_{i\mathrm{R}}^2\omega^3\right)\left(\overbrace{\omega C_{\mathrm{P},i}V_i}^{|I_i|}\right)}_{\text{Direct term (Reflected load)}} + \underbrace{\frac{C_{\mathrm{P},i}}{Z_{\mathrm{L}}}\omega^3\sum_{k=1\neq i}^{n-1}L_{ni}L_{k\mathrm{R}}\left(\overbrace{\omega C_{\mathrm{P},k}V_k}^{|I_k|}\right)}_{\text{Direct term (Double reflected load)}} \qquad (1)$$

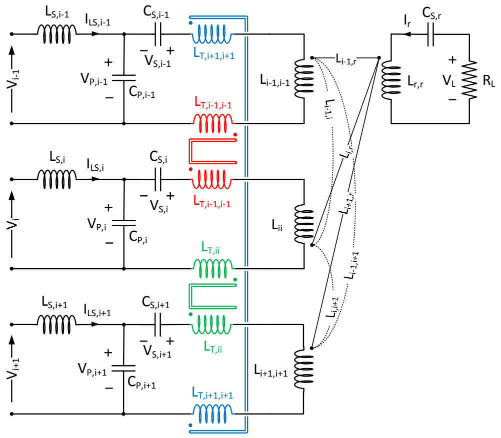


Fig. 6. Circuit diagram of the refined LCC compensator in the MTWPT system.

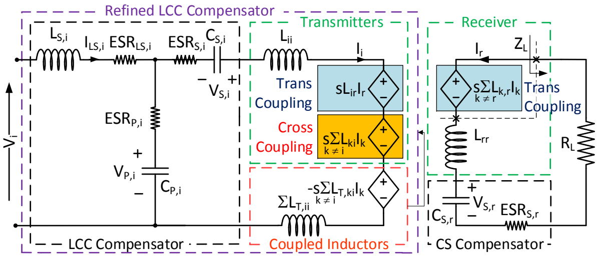


Fig. 7. The equivalent circuit diagram for one transmitter of the four-coil MTWPT system which is equipped with a refined LCC compensator.

counter effect of another artificially made mutual inductance amongst the cross coupled coils, known as CPIs. CPIs are two coupled inductors that are meant to decouple the cross coupled transmitters. The compensating effect of CPIs are shown in Fig. 7 and (1). Therefore, to cancel out the effect of cross couplings, the sum of the quadrature terms of **Cross coupling** and **CPI compensation** in (1) must be equal to zero.

The mutual inductance of a CPI connected to the transmitters k and i ($L_{\mathrm{T},ki}$) can be tuned to compensate the average of the cross coupling profile ($\overline{L_{ki}}$). For example, the variation of the cross coupling terms with respect to the receiver position is shown in Fig. 2(b), where the average value of each cross coupling term can be used to design the CPIs. Moreover, Pantic et al. [11], propose some tuning steps to fully satisfy soft switching conditions, considering the presence of harmonics at the square wave output voltage of the converter. Therefore, with the use of CPIs to compensate the cross couplings, the tuning steps of the refined LCC network can be summarized as follows:

1) Find the cross couplings among the transmitters.
2) Tune the CPIs with a mutual inductance equal to but opposite of the cross couplings, preferably with the same number of turns in primary and secondary sides.
3) Consider the effect of the primary and secondary self-inductances of CPIs in tuning the series capacitor of the LCC filter, based on [11].

In the next section, the experimental results for the given MTWPT system are presented and analysed.

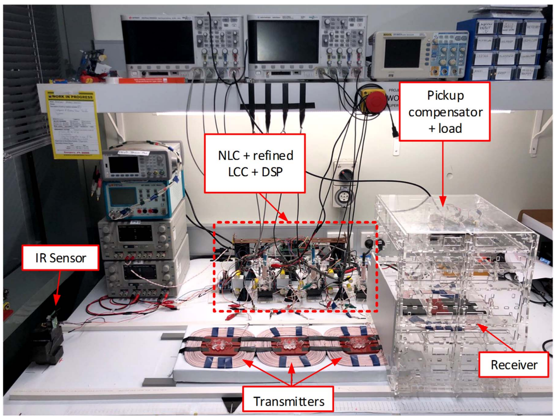


Fig. 8. The experimental setup to study the effect of CPIs on soft switching.

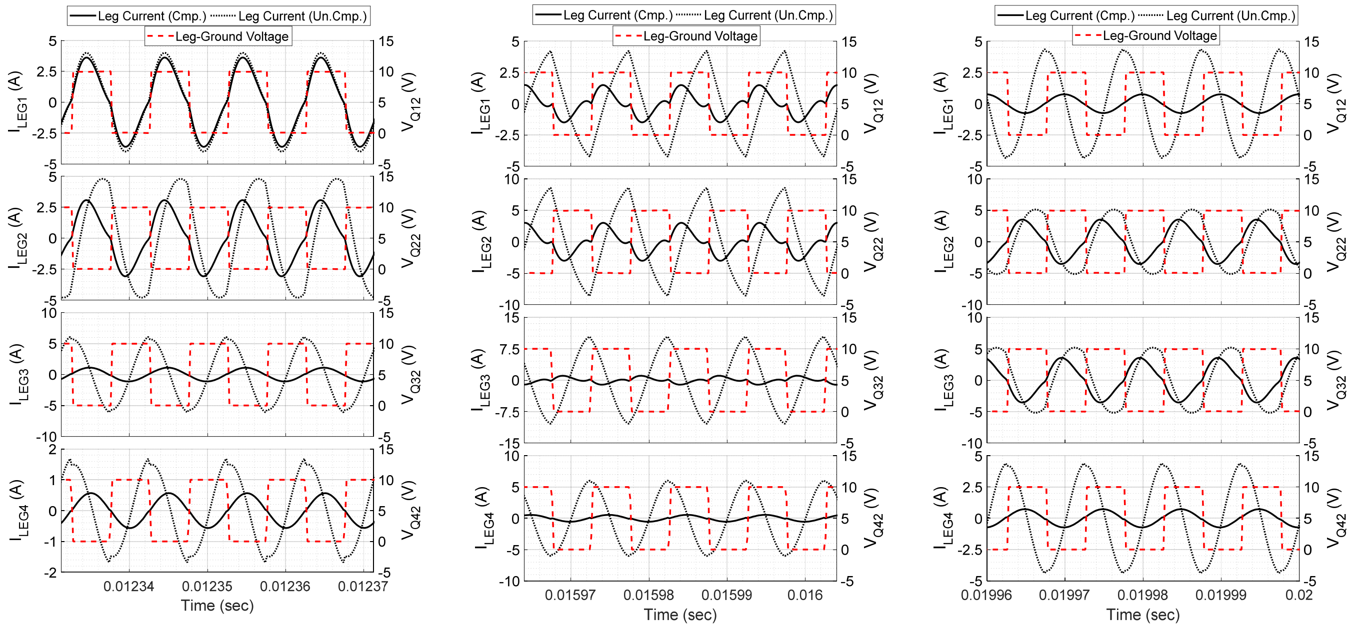
IV. EXPERIMENTAL AND SIMULATION RESULTS

In this section, the MTWPT system is built, as shown in Fig. 8, with the specifications given in TABLE. I. The simulated and experimental results for three modes of operation are also shown in Figs. 9 and 10 respectively.

Therefore, regardless of the pickup position, and the converter modes of operation to excite different transmitters, soft switching can be met using a refined LCC compensator.

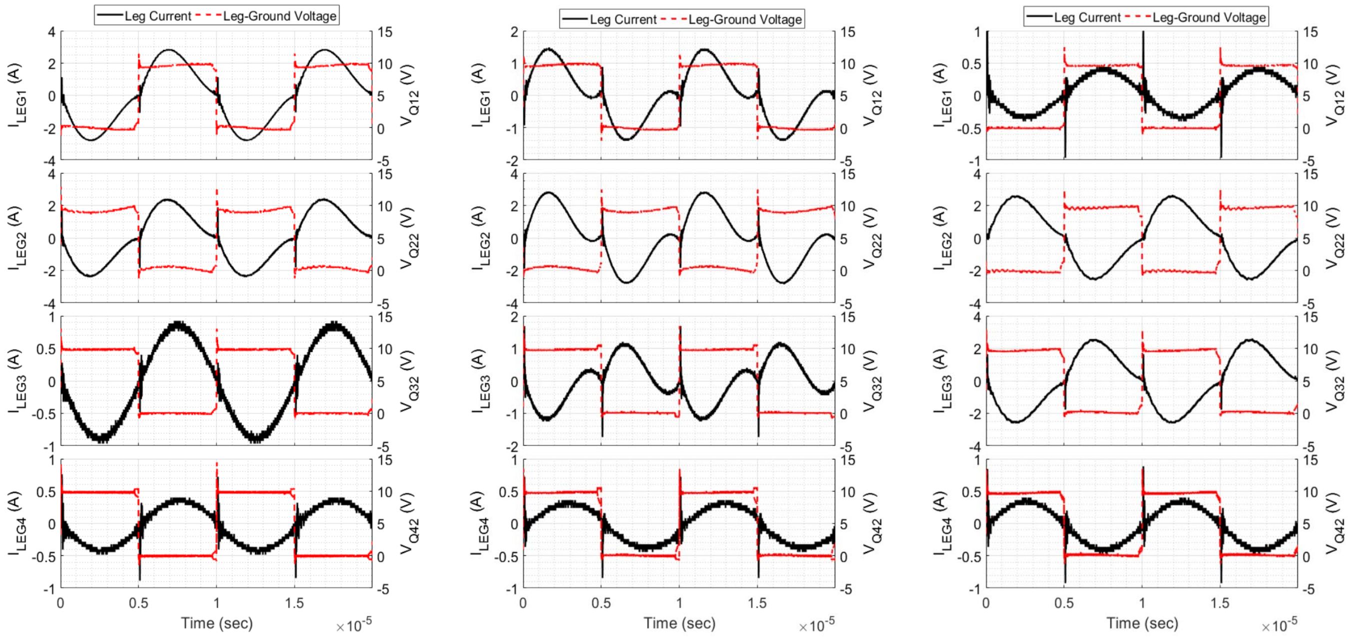
V. CONCLUSION

A simple approach of using coupled inductors (CPIs) to compensate the undesirable effect of cross couplings in multi-transmitter wireless power transfer (MTWPT) systems on the switching of converters is presented in this paper. CPIs create a constant mutual inductance which opposes the cross couplings amongst the transmitters. To study the influence of the cross couplings and CPIs, a four-coil MTWPT system, consisting



X(A) X(B) X(C)

Fig. 9. Simulated leg currents for the refined LCC compensated system in solid black line, and conventional LCC compensated system in dashed black line, which are compared with their corresponding leg-to-ground voltages for different positions of X(A), X(B), and X(C), shown in Fig. 2.



X(A) X(B) X(C)

Fig. 10. Experimental results of the leg currents and leg to ground voltages at different positions of X(A), X(B), and X(C), shown in Fig. 2.

of three transmitters and one receiver is considered as a case study. The system resembles a closely spaced dynamic charger in electric vehicle applications. As in the given system the variation of cross couplings regarding the pickup displacement is negligible, the proposed approach can effectively cancel out the cross couplings. Therefore, using this approach, it is possible to take the advantage of closely spaced MTWPT systems in forming an effective transferred power profile, without the disruption of soft switching resulted by cross coupling amongst the transmitters. The proposed concept is experimentally tested using a laboratory prototype, and the results confirm the theoretical expectations.

TABLE I

SIMULATION AND EXPERIMENTAL SPECIFICATIONS.

Parameter	Value
Track ferrite length (cm)	$\mathrm{TF} = 60.9$
Track transmitter(s) length (cm)	$[\mathrm{TT}_1, \mathrm{TT}_2, \mathrm{TT}_3] = 20.3$
Pickup receiver width (cm)	$\mathrm{TD} = 19.5$
Track coil expansion (mm)	$[\mathrm{TC}_{\mathrm{t1}}, \mathrm{TC}_{\mathrm{t2}}, \mathrm{TC}_{\mathrm{t3}}] = 44$
Track transmitter number of turns	$[\mathrm{N}_{\mathrm{t1}}, \mathrm{N}_{\mathrm{t2}}, \mathrm{N}_{\mathrm{t3}}] = 16$
Pickup ferrite length (cm)	$\mathrm{RF} = 20.3$
Pickup receiver length (cm)	$\mathrm{PR} = 20.3$
Pickup receiver width (cm)	$\mathrm{PD} = 22$
Pickup coil expansion (mm)	$\mathrm{PC} = 31$
Pickup receiver(s) number of turns	$\mathrm{N}_{\mathrm{r}} = 11$
Ferrite thickness (mm)	$\mathrm{T} = 7$
Pickup - track gap distance (cm)	$\mathrm{G} = 12.5$
Ferrite relative permeability	2300 (N97)
Maximum track self-inductance (uH)	$[L_{11} = L_{33}, L_{22}] = [92.2, 94.6]$
Maximum track cross couplings (uH)	$[L_{12}, L_{23}, L_{13}] = [14, 5]$
Maximum pickup self-inductance (uH)	$L_{\mathrm{r}} = 53.9$
WPT frequency (kHz)	$f = 100$
Track LCC series inductor (uH)	$L_{\mathrm{S},i} = 15.9$
Track LCC parallel capacitor (nF)	$C_{\mathrm{P},i} = 330$
Track LCC series capacitor (nF)	$C_{\mathrm{S},i} = 20.62$
Track CPI self-inductance (uH)	$[L_{\mathrm{T1}} = L_{\mathrm{T3}}, L_{\mathrm{T2}}] = [20, 17.6]$
Track CPI mutual-inductances (uH)	$[L_{12}^{*} = L_{23}^{*}, L_{13}^{*}] = [14, 5]$
Pickup series capacitor (nF)	$C_{\mathrm{Sr}} = 47$
Pickup coil resistance (Ohm)	$R_{\mathrm{CP}} = 0.076$
Transmitter coil resistance (Ohm)	$R_{\mathrm{CT}} = 0.085$
Load (Ohm)	$R_{\mathrm{L}} = 9$

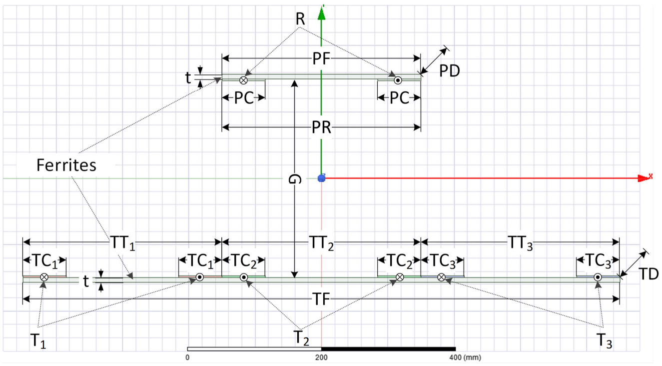


Fig. 11. Geometric representation of the four-coil MTWPT system.

APPENDIX

TABLE. I shows the specifications used to simulate and built the four-coil MTWPT system. To ease finding out the dimensions, Fig. 11 shows the location of the labels shown in TABLE. I.

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