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# Design Simulation and Analysis of Dynamic Wireless Charging Methodology for Electric Vehicles

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**ABSTRACT:** This paper includes detailed design simulation for a 60 kW wireless power transfer charging system for electric vehicles operating at the resonant frequency of 85 kHz. The study includes details about the resonant inductive wireless power transfer system, coil shapes and compensation topologies required in the wireless power transfer setup. A brief about the DDP type coil design in the Ansys Maxwell software and the fabrication of the LCC compensation network in the Ansys Maxwell Simplorer is mentioned. Through the AC and Transient (TR) Analysis, the system parameters viz. voltage, current and power transfer is simulated to achieve optimum system efficiency of 90%.

**KEYWORDS:** Dynamic wireless power transfer (DWPT), coil shapes, DDP pad, aluminum shielding, coupling coefficient, compensation topologies, LCC type compensation, misalignment

## I. INTRODUCTION

The transportation industry consumes 29% of the energy out of which gasoline amounts for 56% of the transportation fuel. To reduce the pressure on conventional fuels, Electric Vehicles (EVs) are the best alternative. However, the major challenge in implementing the EVs is limited range. The range can be outstretched by bracing up the battery capacity which eventually ends up giving bulky, expensive battery architecture. The possible solution to this is to charge the vehicle while moving and this is referred to as "Dynamic Wireless Power Transfer (DWPT)" [1]. For a battery operated electric vehicle (BEV), there are various wireless charging methods viz. capacitive wireless power transfer (CWPT), magnetic gear wireless power transfer (MGWPT), traditional inductive power transfer (IPT) and the most efficient Resonant Wireless Power Transfer (RIPT) method. DWPT can be implemented either with long tracks or with small segmented coils laid on the roads, the later requiring less complex circuit and having overall high efficiency. There are various coil types viz. circular, square, hexagonal, double-D pad (DDP), double-D quadrature pad (DDQP) and bipolar pad (BP), etc [2]. The coil shape least tolerant to misalignment is DDP and the same has been discussed briefly. The frequency range for DWPT is between 10 kHz to 150 kHz and the operating principle is based on Ampere's Circuital law and Faraday's law of induction which explains the interrelation between current carrying conductor and time varying magnetic flux. The ratio of mutual flux to the total flux, which is the coupling coefficient  $k$  lies between 1 to 3% in case of EVs. For improving the coupling and compensating the inductive leakage, capacitive compensation is provided on both the coils. Compensating networks consisting of capacitors are made to resonate with the coil inductance, thus forming a resonant inductive link. Depending upon the positioning of capacitors and inductors with the self inductances of the ferrite coils, there are different types of compensations viz. Series Series (S-S), Series Parallel (S-P), Parallel Series (P-S), Parallel Parallel (P-P) and LCC compensation. The variation in the efficiency for LCC with the variation in mutual inductance is very steady over long ranges and therefore this compensation topology has been preferred.

II. BLOCK DIAGRAM OF DWPT

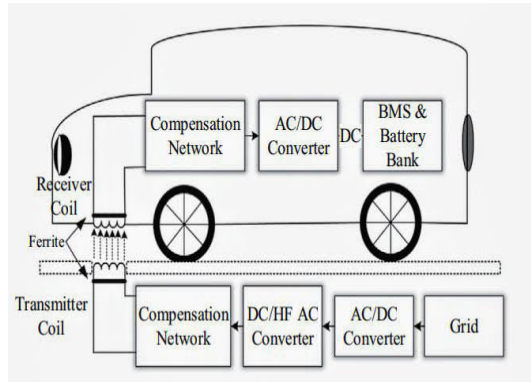


Fig 1 Typical EV wireless charging system conceptual diagram [Source:-“Review of static and dynamic wireless electric vehicle charging system” by Chirag Panchal]

As shown in Fig 1, the setup mainly includes the transmitting coil which is embedded in the charging pads fixed along the road and the receiving coil which is present in the vehicle. At the transmitting side, the supply from the grid is converted into DC using the AC/DC converter and then this DC is converted to high frequency AC signal by means of high frequency AC converter. At the receiving side of the coil, the oscillating magnetic flux is converted to High Frequency AC signal and the AC to DC converter converts this signal to stable DC supply which is then used to charge the battery pack. Ferrite coils of different shapes are present on transmitter and receiver coils to avoid harmful leakage flux and promote uniform flux distribution with tolerable misalignment [3].

III. RESONANT INDUCTIVE POWER TRANSFER

The working principle of RIPT is based on the Ampere’s circuital law and Faraday’s law of induction [4]. The primary and secondary coils are linked by inductive coupling. The subscript P and S refers to primary and secondary coils, respectively. When a time varying current is applied to the primary coil, a time varying flux of the same frequency is produced in the region surrounding the primary. The strength of the magnetic field around a closed path is directly proportional to the current carried by the coil and is given by Ampere’s law as

$$\oint_l H \cdot dl = \int_s J \cdot ds \quad (1)$$

If the currents are carried by wires in a coil with N turns, then the simplified equation is

$$\oint_l H \cdot dl = N_p I_p \quad (2)$$

where ‘H’ is the magnetic field strength,  $N_p$  is the number of turns while  $I_p$  is the current flowing in the primary coil, and  $l$  is the length of the circumference of the closed path. An emf get induced in the secondary coil, when the time varying flux links with it and is given by Faraday’s law of electromagnetic induction as,

$$e_s = N_s \frac{d\phi_m}{dt} \quad (3)$$

The coupling coefficient  $k$  relates common flux to total flux and is given by,

$$k = \frac{\phi_m}{\phi_m + \phi_{lp}} \quad (4)$$

Where  $\phi_p = \phi_m + \phi_{lp}$  is the total flux produced by the primary coil,  $\phi_m$  is the mutual flux and  $\phi_{lp}$  is the leakage flux. Thus, the induced emf in the secondary coil in terms of coupling coefficient is given by

$$e_s = k N_s \frac{d\phi_p}{dt} \quad (5)$$



The systems are of two types- loosely and tightly coupled, based on values of  $k$  [1]. To allow the inconsistencies on the road, better clearance between road and vehicle becomes mandatory. This large air gap eventually results in large leakage flux thus reducing the coefficient of coupling to maximum 3% for the EV application. Such a system is a loosely coupled system and leads to poor transfer of power. To improve coupling and compensate leakage inductance, capacitive compensation in primary and secondary winding is required.

#### IV. DOUBLE –D PAD (DDP)

Planar coils are of two types- Polarized Pads (PP) and Non-Polarized Pads (NPP) [1]. NPPs are single coil pads which can couple and generate only perpendicular components of the flux. NPP's are the traditional shaped coils, such as circular, square, rectangular, hexagonal. PP's are multiple coil pads which can couple and create the parallel, perpendicular or both the component of flux. However, PPs also generate flux at the back of the pad. Thus, when an Aluminium backing plate is added it generates more loss, in the form of eddy current [4]. As a solution to this; single sided multiple coils polarized pads were modelled and the types were: double-D pad (DDP), double-D quadrature pad (DDQP) and bipolar pad (BP).

The DDP pad combines the advantage of both flux pipe as well as circular pad. The coils are placed on the top of the ferrite and the Aluminium shielding is given beneath the ferrite so that the quality factor remains unaffected [1]. Thus, the DDP design has higher coefficient of coupling, low losses in Aluminium shielding and lower leakage flux and also the flux height is proportional to half the length of the pad. Another advantage is, when coupled with another DD pad, each section of the primary coil is linked with the corresponding section of the secondary coil, and the voltage at the pick-up terminals is the sum of the voltages induced in the two sections.

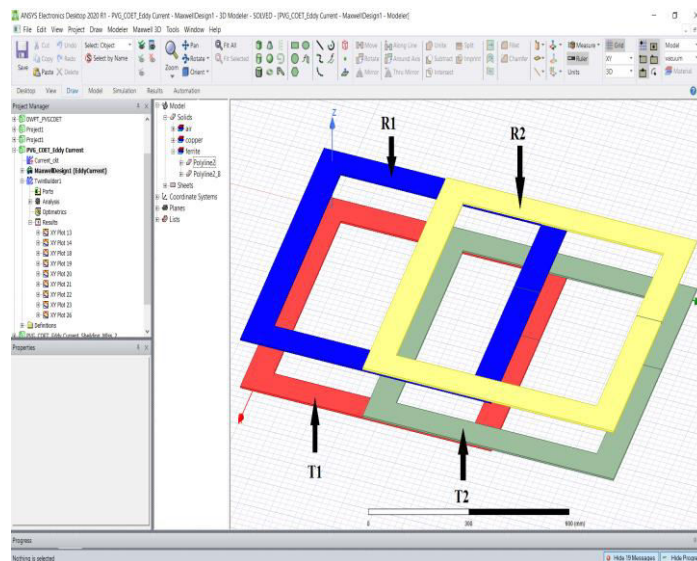


Fig 2 DDP coil modeled in the Ansys Maxwell RS 3D

As shown in Fig 2, the coils at the top, blue and yellow are receiving coil R1 and R2 respectively. Similarly, the coils at the bottom, red and green are transmitting coils T1 and T2 respectively. The dimensions for the coil designed are 800 x 800 mm. Height for each coil is 4mm and the width of the strip is 80mm. Material used for the coil is Copper and the boundaries are insulating. The turn's ratio for transmitter pad to receiver pad is 7:5. An air gap of 120 mm is maintained in between the transmitter and receiver pad.

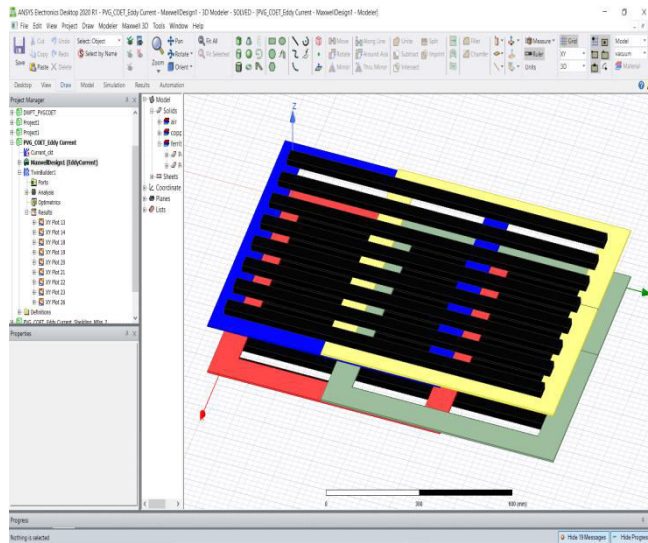


Fig 3 DDP coil with the ferrite bars modeled in the Ansys Maxwell RS 3D

Fig 3 shows the ferrite bars in black. There are total 16 such bars used, 8 on the transmitting side and 8 on the receiving side. Length of each bar is 1090mm, width is 40mm and height is 16mm.

Thus by simulating the coil design, for a DWPT system excited by 230 V AC supply operating at 85 kHz resonance frequency; using the 3D Transient Magnetic Analysis, the values for self-inductance, resistance, mutual inductance and coupling coefficient provided directly by the Ansys Maxwell software are as follows-

TABLE I. VALUES OBTAINED FOR SELF INDUCTANCE AND RESISTANCE

Parameters	R1-R1	R2-R2	T1-T1	T2-T2
Self Inductance ( $\mu\text{H}$ )	65.63	66.78	130.89	127.41
Resistance ( $\text{m}\Omega$ )	3.81	3.81	7.45	7.45

TABLE II. VALUES OBTAINED FOR MUTUAL INDUCTANCE AND COUPLING COEFFICIENT

Parameters	T1-R1	T2-R2
Mutual Inductance ( $\mu\text{H}$ )	49.60	49.79
Coupling Coefficient	0.5351	0.5397

### V. COMPENSATION TOPOLOGIES

Compensation method is essential because of its functions of adjusting resonant frequency, minimizing the volt-ampere rating of power supply, improving coupling and power transfer capability and achieving high efficiency [5]. Four basic compensation topologies, namely, series-series (SS), SP, PS, and PP, are widely adopted for EV applications. They are named by the way the compensated capacitors are connected to the primary and secondary coils. Among these four topologies, only the SS compensation topology has the characteristics that the resonant frequency is independent of the coupling coefficient and load [6]. This feature is essential for dynamic charging as the coupling coefficient varies along with the change in the relative position between primary and secondary coils.

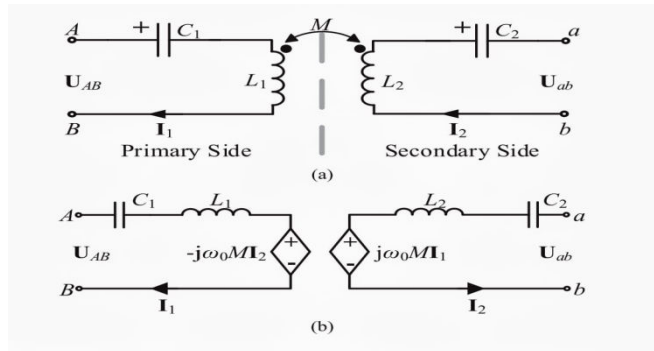


Fig 4 (a)SS compensation topology. (b) Dependent voltage equivalent circuit model.[Source:-Weihan Li, Student Member, IEEE, Han Zhao, Junjun Deng, Member, IEEE, Siqi Li, Member, IEEE, and Chunting Chris Mi, Fellow, IEEE, “Comparison Study on SS and Double-Sided LCC Compensation Topologies for EV/PHEV Wireless Chargers ”

In fig 4(a) & 4(b),  $U_{AB}$  is taken as reference input voltage and is in phase with current  $I_1$ . Whereas  $U_{ab}$  is equivalent battery voltage and is in phase with current  $I_2$ .

SS-compensated wireless charger is a constant current source and can be controlled by the input voltage in practice. SS-compensated wireless charger system with ideal components has no reactive power in the system, and the power factor  $P F$  is unity. The output and input real power can be obtained as given in [6]-

$$P_{out-tuned} = P_{in-tun} = R_e(U_{AB} I_1^*) = \frac{1}{\omega_0 M} U_{AB} U_{ab} \quad (6)$$

where  $I_1^*$  is the complex conjugate of  $I_1$  and  $M$  is the mutual inductance. Thus, the output power is inversely proportional to mutual inductance  $M$ . Mutual inductance will reduce when the primary and secondary coils are misaligned. And thus position detection becomes very important to ensure that mutual inductance  $M$  is maintained within a certain range.

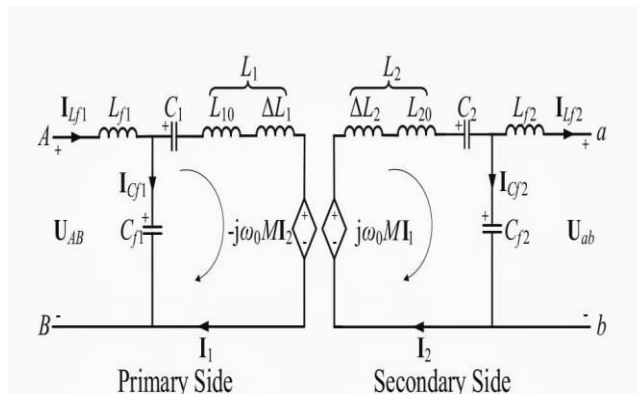


Fig 5 Double sided LCC compensation topology equivalent circuit model. [Source:-Weihan Li, Student Member, IEEE, Han Zhao, Junjun Deng, Member, IEEE, Siqi Li, Member, IEEE, and Chunting Chris Mi, Fellow, IEEE, “Comparison Study on SS and Double-Sided LCC Compensation Topologies for EV/PHEV Wireless Chargers”]

The double sided LCC compensation topology has an additional series inductor and an additional parallel capacitor for both transmitting and receiving sides compared with the SS compensation topology.

The input-output power equation is obtained as [6]-

$$P_{out-tuned} = \frac{M \cdot U_A \cdot U_{ab}}{\omega_0 L_{f1} L_{f2}} \quad (7)$$

where  $M$  is the mutual inductance. Thus, for a double-sided LCC compensation topology,  $L_{f1}$  or  $L_{f2}$  can be used as another consideration to design the system with desirable efficiency and this is an advantage over the SS topology.

The efficiency of SS topology is higher when the mutual inductance is higher, whereas the efficiency of LCC topology is higher at minimum values of mutual inductance. The variation in the efficiency with the variation in mutual inductance is steady over a long range for LCC topology because the losses on the compensation network increase while those at the primary coil decrease when the mutual inductance increases [6]. Thus, even though the efficiency of LCC is less than SS for higher values of mutual inductance, it is the preferred configuration due to its steadily varying percentage efficiency as variation in mutual inductance is obvious for any electric vehicle owing to the irregularities on the road surface.

### VI. LCC COMPENSATION

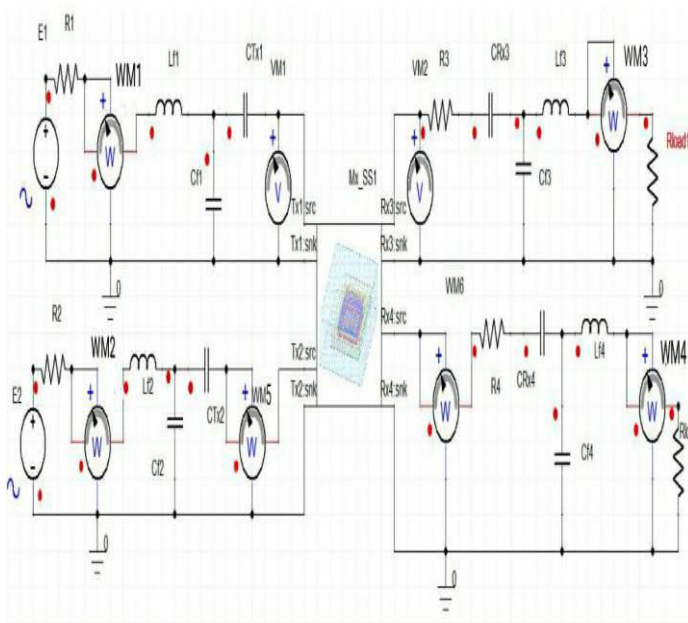


Fig 6 LCC Compensation designed in Ansys Maxwell Simplorer

As shown in Fig 6,  $L_{f1}$  and  $L_{f2}$  are the inductors on the transmitting side and  $L_{f3}$  and  $L_{f4}$  are the inductors on the receiving side. All these inductors are assumed to be  $10 \mu\text{H}$  each ( $L_f$ ).  $L_1$  and  $L_2$  are the self-inductances of transmitting coils  $T_1$  and  $T_2$ , whereas  $L_3$  and  $L_4$  are the self-inductances of the receiving coils  $R_1$  and  $R_2$  respectively. These values are directly provided by the Ansys Maxwell software after simulating the coil design and are mentioned in Table I.  $WM1$  and  $WM2$  are transmitter side wattmeter and  $WM3$  and  $WM4$  are receiving side wattmeter. Following relations are used to calculate the remaining parameters in the LCC compensation network. [4]. All the calculations are performed at the resonant frequency of 85 kHz.

$$L_{(1,2)} - L_f = \frac{1}{\omega_0^2 C_{Tx(1,2)}} \quad (8)$$

$$L_{(3,4)} - L_f = \frac{1}{\omega_0^2 C_{Rx(1,2)}} \quad (9)$$

$$L_f C_f = \frac{1}{\omega_0^2} \quad (10)$$

Thus by using the above relations the values actually calculated for the compensating capacitors on the transmitting side ( $C_{Tx1}$ ,  $C_{Tx2}$ ) and receiving side ( $C_{Rx1}$ ,  $C_{Rx2}$ ) are mentioned in Table III.



TABLE III. VALUES CALCULATED FOR COMPONENTS IN THE LCC NETWORK

Components	Values Calculated
Lf	10 μH
Cf	3.51 nF
C <sub>Tx1</sub>	2.9 nF
C <sub>Tx2</sub>	2.986 nF
C <sub>Rx1</sub>	6.30 nF
C <sub>Rx2</sub>	6.17 nF

Thus for the system modeled, using the LCC compensation, a coupling coefficient of 0.53 is achieved.

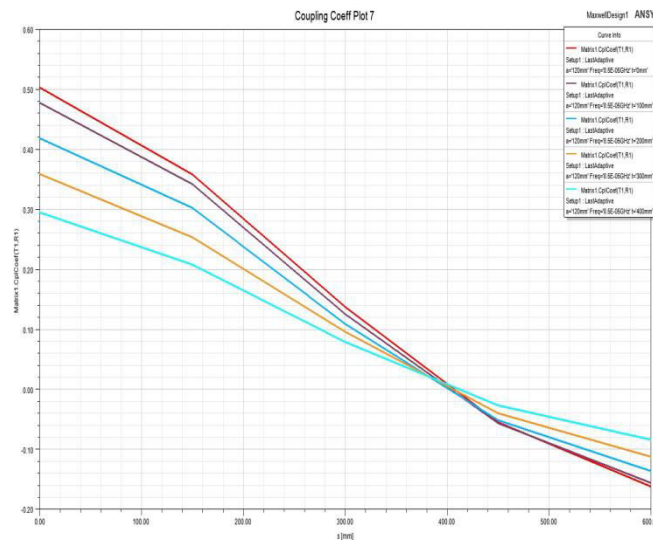


Fig 7 Graph of variation of coupling coefficient for various misalignments

Fig 7 shows the graph of variation in the coupling coefficient obtained for the system designed at various misalignment levels. At 120 mm air gap, for a perfectly aligned system, the coupling coefficient obtained is 0.53 as shown by the red line. The purple, blue, yellow and cyan blue line show the variation of coupling coefficients when there is a horizontal misalignment of 100mm, 200mm, 300mm and 400mm between the transmitter and receiver track. Thus for 400mm misalignment, i.e. when the vehicle is partially on 800mm wide track, the coupling coefficient and is least approximately equal to 0.3.





**VIII. PARAMETERS FOR THE SYSTEM DESIGNED**

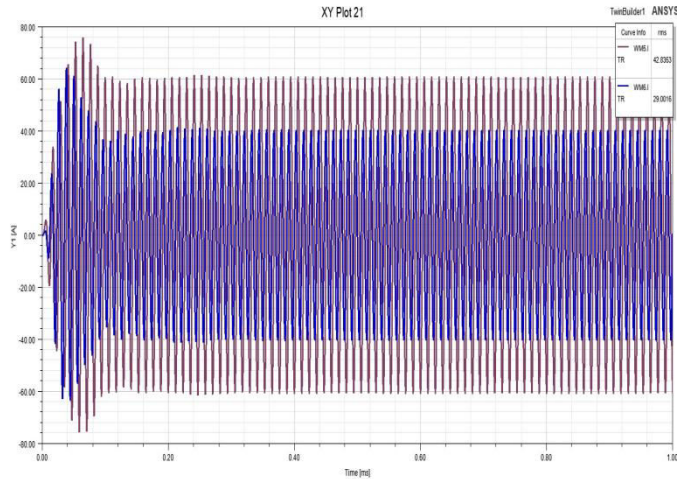


Fig 8 Plot of Input and Output Current obtained using Transient (TR)Analysis

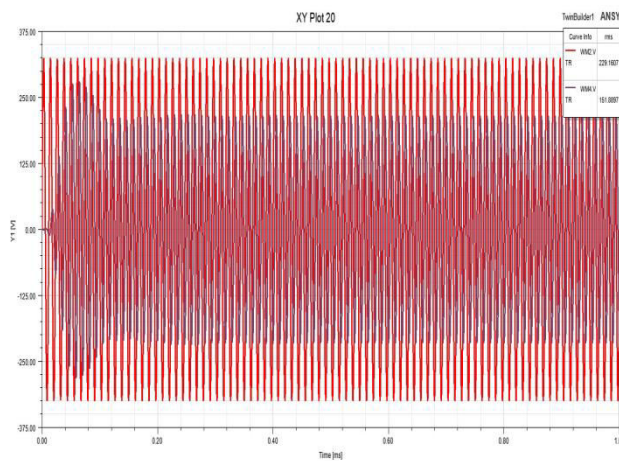


Fig 9 Plot of Input and Output voltage obtained using Transient (TR)Analysis

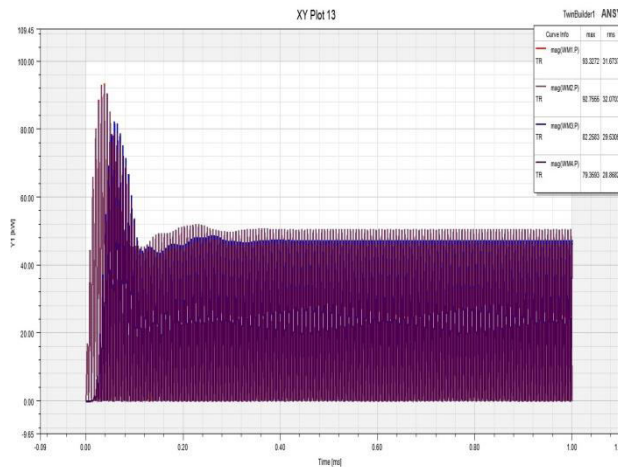


Fig 10 Plot of Input and Output Power obtained using Transient (TR)Analysis



TABLE IV. VALUES FOR VOLTAGE AND CURRENT

Sr. no	Parameter	Transmitter Side	Receiver Side
1	RMS Voltage(V)	229.16	151.89
2	RMS Current (A)	42.85	29.00

TABLE V. VALUES FOR TRANSMITTER AND RECEIVER SIDE POWER

Power	RMS value in kW	RMS value in kW	Net power in kW
Transmitter side	WM1-31.67	WM2-32.67	WM1+WM2=64.34
Receiver side	WM3-29.53	WM4-28.87	WM3+WM4=58.4

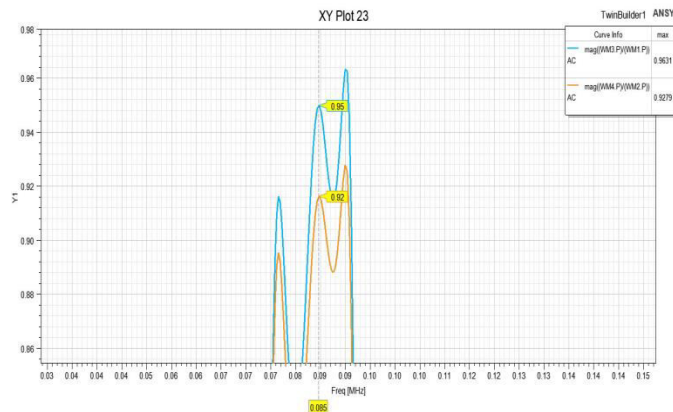


Fig 11 Plot for power transfer efficiency between T1-R1 and T2-R2 obtained using AC analysis

**IX. CONCLUSION**

Thus, power transfer efficiency achieved for the modelled system operating at 230 V AC supply and 85 kHz resonance frequency is 95% between coils T1-R1 and 92% between coils T2-R2.

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