ON MAGNETICALLY COUPLED COILS PARAMETER CALCULATION

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Abstract. *ANSYS Q3D Extractor tool (AQ3DE), using the quasi-static solvers (method of moments, integral equations and FEMs), is very efficient for computing and simulating two- and three-dimensional electromagnetic field. This simulation is used to extract parameters of interest, such as: resistance (R), conductance (G), self-inductance (L), mutual inductance (M) and capacitance (C). These parameters can be further used to optimize and to obtain automatically the design of a wireless power transfer systems (WPTS). The resulting matrices allow the generation of new matrices for any selected parameters. To complete the analysis, the model which is computed will be exported as an equivalent circuit. In this paper, starting from a given WPTS, using AQ3DE tool, the parameters of interest (R, G, L, M, C) were automatically calculated, and the SPICE equivalent circuit was obtained. The analysis was performed for two different distances between the emitter and the receiver. The electrical circuit theory was used for the system analysis of magnetically coupled coil (MCC) system. Starting from the parameters extracted by the AQ3DE tool, the performance of the WPTS has been analysed both in time and frequency domain.*

Keywords: ANSYS DesignerSI, AC/DC analysis, SPICE, magnetically coupled coils, optimization, circuit simulation

1. INTRODUCTION

For engineering design and for power electronics domain, one of the most suitable software is ANSYS Q3D Extractor software (AQ3DE) [1]. This software allows the extraction of two- and three-dimensional parameters.

AQ3DE, using the quasi-static solvers (finite element method), is very efficient for computing and simulating two- and three-dimensional electromagnetic field [2]. This simulation is used to extract parameters of interest, such as: resistance (R), conductance (G), self-inductance (L), mutual inductance (M) and capacitance (C). These parameters can be further used to optimize and to obtain automatically the design of a wireless power transfer systems (WPTS). This simulation is used to extract the resistance, conductance, self-inductance, mutual inductance and capacitance (R, G, L, M, C) parameters for an optimal and automatic design of a WPTS [3-6]. In this way a list of the electronic components in a circuit and a list of the nodes (netlist) is automatically generated. The generation of the netlist can be done in various formats such as: ANSYS Simplorer format (.sml) and SPICE format (.cir). The solver will output the matrices of interest (C, G, R, L) and voltage distributions and current distributions. To accelerate the solution, AQ3DE uses the method called fast multipole method (FMM) [1], [7-9].

For higher electromagnetic field operating frequencies, when the radiation is important, AQ3DE uses the full-wave solvers to generate the S, Y, and Z parameters and fields [10-13]. AQ3DET can also generate the parameters S which are further exported in Touchstone format (i.e. a text file which contain the parameter data of an n-port network). The parameters which depend on high frequencies can be simulated using products such as: ANSYS Designer SI or ANSYS Simplorer [1, 2].

DesignerSI is a very accurate design platform. It puts together the circuit simulation and analysis with the analysis of the electromagnetic field. With this powerful tool, the simulation of the integrity of the signal can be handled using different approaches and methods. More, the methods contain optimization algorithms, tuning algorithms, design of experiments (DOE) algorithms, etc. Using AQ3DE solver, a complete package of structures can be characterized and the values of *the R, L, C, G* (Resistance, Inductivity, Capacity and Conductance) matrices are automatically calculated or distributed. The generation of *G* and *C* matrices are performed using the static electromagnetic field analyses [14-18]. To generate *R* and *L* there are used ac and dc analyses. Finally, the software generates a SPICE file that can be exported for analysis with a circuit simulator.

For the given workbench, by analyzing the results, one can choose the most suitable solution (optimal).

In this paper, starting from a given WPTS, using AQ3DE tool, the parameters of interest (R, G, L, M, C) were automatically calculated, and the SPICE equivalent circuit was obtained. The analysis was performed for two different distances between the emitter and the receiver. The electrical circuit theory was used for the system analysis of magnetically coupled coil (MCC) system. Starting from the parameters extracted by the AQ3DE tool, the performance of the WPTS has been analyzed both in time and frequency domain

2. DESCRIPTION OF ANSOFT Q3D EXTRACTOR Q3D (Q2D)

2D and 3D interconnected structures can be fully characterized from electrical and magnetical point of view by using the dedicated software AQ3DE [1, 2].

By using AQ3DE, one obtains the parameters:

- Capacity matrices (C) in static regime;

- Self and mutual inductivities and resistances matrices ($\mathbf{L}$, $\mathbf{M}$, $\mathbf{R}$) in dc analysis;
- Resistances, self and mutual inductivities and resistances matrices ($\mathbf{L}$, $\mathbf{M}$, $\mathbf{R}$) for high frequency ac analysis.

The procedure for computing the parameters of magnetically coupled coils (MCC), involves the following preliminary steps:

- select the analysis to be performed;
- obtain the model;
- provide the material properties;
- identification of the conductive elements;
- specification of the excitation source.

The parameters needed for the circuit are automated generated. The system automatically generates the necessary parameters of the circuit. The MCC parameters identification [6], [11], [15] used in WPTS, is based on Maxwell's equations (general and local forms of the laws).

As a case study, we consider a WPTS, which consist of two coils, magnetically coupled, helix shape (Figure 1).

The two coils form a WPTS. Denote by Tx - the transmitter (transmitting coil) and by Rx - the receiver (receiving coil). Both coils are identical with given parameters:

- helix coil: rectangular section: 1.71 mm x 3.20 mm;
- pitch (distance between two consecutive turns): 2.2 mm;
- 2 layers each having 8 turns in series connection; distance between layers: 2 mm.

Between the two coils the distance can be changed (the results were analysed for $z = 20.2$ mm, respectively $z = 70$ mm).

Figure 1. Two magnetically coupled coils, helix shape.

3. MODELLING PROCESS ALGORITHM

The parameters of interest, $\mathbf{R}$, $\mathbf{G}$, $\mathbf{L}$, $\mathbf{C}$ are computed using AQ3DE. The next steps are performed by the software:

- The structure is divided in finite elements network;
- Inside the structure, the electromagnetic field is computed, function of the selected type of analyses (a source terminal or a single conductor is excited at a given moment);
- The parameters $\mathbf{R}$, $\mathbf{L}$, $\mathbf{G}$ and $\mathbf{C}$ are computed function of the field's values - computed above.

For any selected parameters, new matrices can be obtained based on the previously resulting matrices. For further

analysis, the results will be exported to an equivalent circuit (Figure 2).

The matrix's inputs are computed by the solver. The conductive elements influence the calculation of the parameter's matrices.

After the solution of the field is computed and the corresponding matrices are completely calculated, AQ3DE is performing the analysis of the error. This analysis takes place for any element belonging to a loop of the network.

To obtain an accurate solution, the computation is adapted to be performed on smaller elements.

Figure 2. SPICE equivalent circuit obtained by the Q3D EXTRACTOR simulator.

4. NUMERICAL RESULTS

The obtained numerical results for the proposed case study (Figure 1), are presented in Table 1. The values are given in Ansys format.

Table 1. Parameters obtained with the AQ3DE for $f = 20$ kHz

f

h [mm] (distance between the coils)	C [pF] (capacity matrix)	R [mΩ] (matrix of resistances)	L [nH] (matrix of inductivities)	$k = M / \sqrt{L_1 \cdot L_2}$
20.2	$\begin{pmatrix} 2.9011 & -1.2613 \\ -1.2613 & 2.9022 \end{pmatrix}$	$\begin{pmatrix} 3.3633 & 0.26225 \\ 0.26225 & 3.4022 \end{pmatrix}$	$\begin{pmatrix} 44.928 & 2.5835 \\ 2.5835 & 44.85 \end{pmatrix}$	0.05757
70	$\begin{pmatrix} 2.4635 & -0.5544 \\ -0.5544 & 2.4641 \end{pmatrix}$	$\begin{pmatrix} 3.0806 & 0.0388 \\ 0.0388 & 3.0791 \end{pmatrix}$	$\begin{pmatrix} 45.423 & 0.4072 \\ 0.4072 & 45.408 \end{pmatrix}$	0.00236

In SPICE format the capacities matrices differ from one in Ansys format.

To obtain the SPICE format, we proceed as follows:

$$\begin{aligned} C11_{\text{Spice}} &= C11_{\text{Ansyz}} + C12_{\text{Ansyz}} \\ C12_{\text{Spice}} &= -C12_{\text{Ansyz}} \\ C12 &= C21 \end{aligned}$$

Taking this into account, results the values for the capacities the SPICE format:

$$\begin{pmatrix} 1.6398 & 1.2613 \\ 1.2613 & 1.6409 \end{pmatrix} \begin{pmatrix} 1.90901 & 0.55449 \\ 0.55449 & 1.90961 \end{pmatrix}$$

In Figure 3 is shown the magnetic field strength [A/m] for $z = 20.2\text{mm}$. For $z = 70\text{ mm}$, the magnetic field strength [A/m] is given in Figure 4.

Figure 3. Magnetic field strength, $z = 20.2\text{mm}$

Figure 4. Magnetic field strength, $z = 70\text{mm}$.

5. USE OF ELECTRICAL CIRCUIT THEORY IN THE SYSTEM ANALYSIS OF MCC SYSTEM

In Figure 5, a there is presented the topology of two MCC with series connection, and in Figure 5, b is drawn the operational diagram of the system.

By considering the initial conditions, null, one can replace the magnetic coupling with two current-controlled voltage sources (CCVT)

Figure 5. a) Topology of two magnetically coupled coils system with series connection; b) The operational diagram of the system.

Using AQ3DE, one obtains the parameters corresponding to the MCC. The values are listed below:

$$\begin{aligned} L_1 &= 63.76 \mu\text{H}, L_2 = 32.6 \mu\text{H}, M = 1.5957 \mu\text{H}, \\ k &= 0.35, C_1 = 0.15844 \mu\text{F}, C_2 = 0.31 \mu\text{F}, \\ R_1 &= 0.0925 \Omega, R_2 = 0.0545 \Omega, J_1 = 20 \text{ A}, \\ R_i &= 1.5 \Omega, R_L = 6.0 \Omega, f_0 = 50.1 \text{ kHz}, \\ \omega_0 &= 3.1463e05 \text{ rad/s}, \\ Q_1 &= \omega_0 L_1 / (R_i + R_1) = 12.597 \\ Q_2 &= \omega_0 L_2 / R_2 = 188.1995. \end{aligned}$$

Analyzing the circuits in Figure 5, a and b in time domain for $i = 20\sin(2\pi ft)$ [A], we obtain the results presented in Figure 6 - 8.

Figure 6. i_{L1} and i_{RL} vs. time.

Figure 7. $u_{i,t}$, $u_{L1,t}$, $u_{L2,t}$ and $u_{RL,t}$ vs. time Figure 8. Load power p_{RL} vs. time.

In Figure 9 we analyze the circuit from Figure 5 in frequency domain. Figure 9 depicts the load power (P_{RL}), the input power (P_1) and efficiency η_{21} function of frequency.

Figure 9. P_{RL} , P_1 , $\eta_{21} = 100 \cdot P_{RL}/P_1$ function of frequency

Table 2 shows the maximum values of P_{RL} and the η_{21} with respect to frequency.

Table 2 Load power and efficiency function on frequency

f [kHz]	P_{RL} [kW]	η_{21} [%]
$f_0 = 50.1$	$P_{RL_{f_0}} = 1.65025$	$\eta_{21_{f_0}} = 71.68$
$f_{P_{RLmax}} = 55.132207$	$P_{RL_{f_{P_{RLmax}}}} = 1.8077262$	$\eta_{21_{f_{P_{RLmax}}}} = 73.450565$
$f_{\eta_{21max}} = 55.1322$	$P_{RL_{f_{\eta_{21max}}}} = 1.8077279$	$\eta_{21_{f_{\eta_{21max}}}} = 73.450613$

where:

- $P_{RL_{f_{\eta_{21max}}}}$ ($\eta_{21_{f_{P_{RLmax}}}}$) is the load power (efficiency) for the that frequency which ensures the maximum value of the efficiency (load power).

6. CONCLUSIONS

ANSYS Q3D Extractor tool, using the quasi-static solvers (method of moments, integral equations and FEMs), is very efficient for computing and simulating two- and three-dimensional electromagnetic field. This simulation is used to extract parameters of interest, such as: resistance (R), conductance (G), self-inductance (L), mutual inductance (M) and capacitance (C). These parameters can be further used to optimize and to obtain automatically the design of a wireless power transfer systems (WPTS).

The resulting matrices allow the generation of new matrices for any selected parameters. To complete the analysis, the model which is computed will be exported as an equivalent circuit. In this paper, starting from a given WPTS, using ANSYS Q3D Extractor tool, the parameters of interest (R, G, L, M, C) were automatically calculated, and the SPICE equivalent circuit was obtained. The analysis was performed for two different distances between the emitter and receiver ($z = 20.2\text{mm}$ and $z = 70\text{mm}$ respectively).

We also used electrical circuit theory in the system analysis of magnetically coupled coil system. Starting from the parameters extracted by the ANSYS Q3D Extractor tool, the performance of the WPTS has been analysed both in time and frequency domain.

7. ACKNOWLEDGMENTS

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