Compensation Considerations for Bidirectional Inductive Charging Systems of Electric Vehicles with Coil Positioning Flexibility

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Bidirectional inductive power transfer systems enable power transfer between stationary electricity source and movable consumers in each direction through electromagnetic coupling. Due to its complexity, a mathematical model is required to design and to control these systems. This paper presents the mathematical analysis and frequency domain analysis for two different compensated (series-series and parallel-parallel) bidirectional inductive power transfer systems. The paper contains the modeling procedure of bidirectional inductive power transfer system's coils in the frequency domain. The prediction of its equivalent circuit values, magnetic stray field values and coil positioning tolerance are determined as well using the JMAG field simulation software. Furthermore, the transmission characteristics and the efficiency of the two compensation topologies are discussed.

***Index Terms*—Electric vehicles, inductive power transmission, electromagnetic coupling, frequency-domain analysis, air gap.**

I. Introduction

Inductive Power Transmission (IPT) is an established technology to deliver power to mobile devices. It is used for medical devices, for the supply of sensor modules or for consumer electronics [1]-[5]. Over the last few years, IPT technology is widely discussed as a charging method for the traction batteries of electric vehicles (EV) and hybrid electric vehicles (HEV) [6]-[7]. The distributed energy storage is essential for the intelligent power grid. By using the energy stored in the batteries, EV and HEV can operate as moving energy resources, able to inject electrical energy back into the power grid.

II. The Resonant Transmission System

A Bidirectional Inductive Power Transfer (BIPT) system consists of a number of components. The power coupling between ground and vehicle is established by the stationary transmitter unit and the on-board receiver unit. The receiver unit is connected to the vehicle's battery. Depending on the power flow's direction, its characteristic changes, either power supply unit (single phase or three phase) or load.

The system operates in principle like a conventional transformer with the difference, that the electromagnetic circuit is closed via a large air gap. However, a large air gap leads to high leakage inductance values and to a small electromagnetic coupling as well. Hence, the high leakage inductivities have to be compensated by capacitors. The system should be designed symmetrically due to its bi-directional application characteristics. Thus, only two compensation topologies (series-series and parallel-parallel) are possible.

For the simulations, the specifications of special materials like litz wire and ferrite cores are deployed. The results are obtained with flat coils possessing the following coil diameter on both sides d_{inner} = 240 mm, d_{outer} = 270 mm. The vertical distance between coils is 100 mm. The primary and the secondary coils are modeled as a circular ring.

III. Frequency Domain Analysis

A. Series-series compensation

It is necessary to design an efficient and an accurate model to control the electric system. Anyway, it is difficult to analyze the dynamics of electric systems, including switch devices, since they incorporate continuous time dynamics as well as discrete time events.

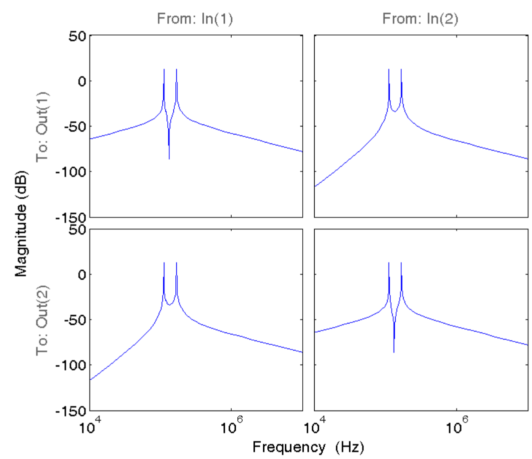

Fig. 1. Behavior of transfer function matrix of series-series compensation.

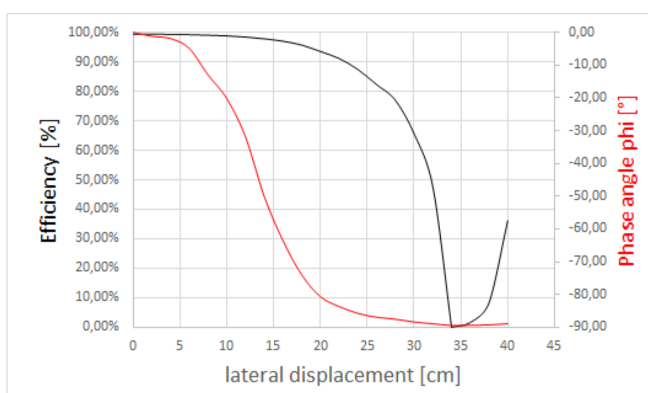

Fig. 2. Changing of efficiency and phase angle at lateral displacement for series-series compensated BIPT (simulated with JMAG).

Fig. 1 displays the behavior of each element H_{11}, H_{12}, H_{21} and H_{22} of the transfer function. It is observed that H_{11} and H_{22} possess similar behaviors. These results show that the derived state space system is able to be the basis of a robust bidirectional power transfer controller. For H_{12} and H_{21} the same characteristic is obtained as well.The main and the leakage inductivities of the coils are determined with the lateral coil misalignment. The efficiency results and the changing of phase angle are shown in Fig. 2 and in Fig. 4.

Due to the limited text length, the mathematical models and the transfer functions cannot be presented but the behavior of the transfer function matrix derived from these models is demonstrated.

B. Parallel-parallel compensation

The behavior of each element H_{11}, H_{12}, H_{21} and H_{22} of the transfer function for parallel-parallel compensation is shown in Fig. 3. Compared to series-series compensation topology, the parallel-parallel compensation topology is disordered.

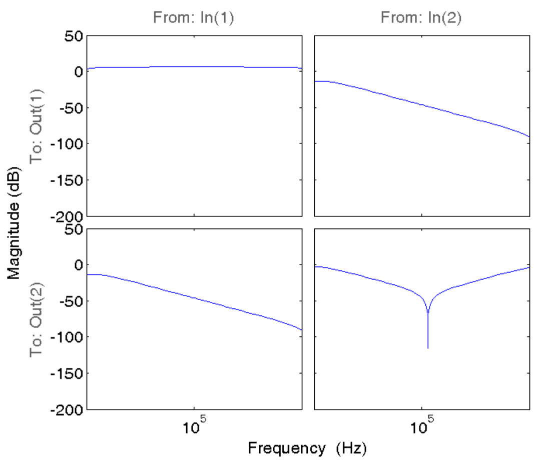

Fig. 3. Behavior of transfer function matrix of parallel-parallel compensation.

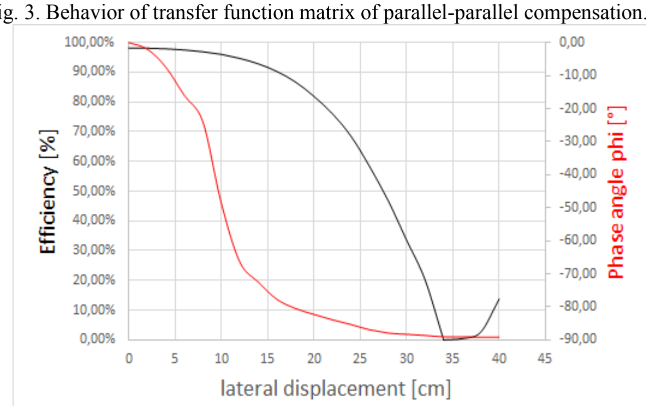

Fig. 4. Changing of efficiency and phase angle at lateral displacement for parallel-parallel compensated BIPT (simulated with JMAG).

IV. Frequency Tolerance

The resonance frequency of the two IPT systems changes with the lateral or vertical coil misalignment. It is observed, that in some cases more resonant frequencies occur than the desired one. The transmission characteristic, described by the phase angle φ and the amount $|Z|$ of the system's impedance Z, is heavily nonlinear dependent on the electrical load R connected to the secondary coil. The phase angle φ illustrates the system's resonance frequency as shown in Fig. 5 and in Fig. 6.

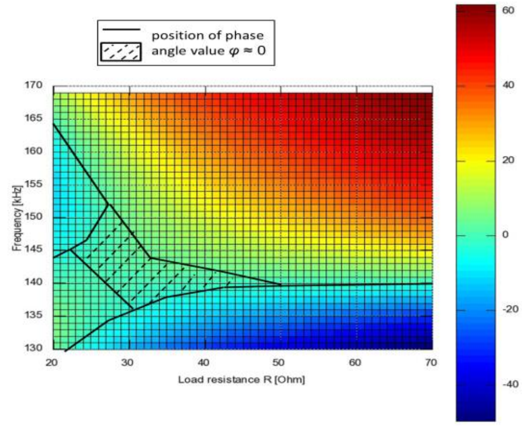

Fig. 5. Phase angle characteristic of a series-series compensated BIPT system dependent on load resistance and frequency.

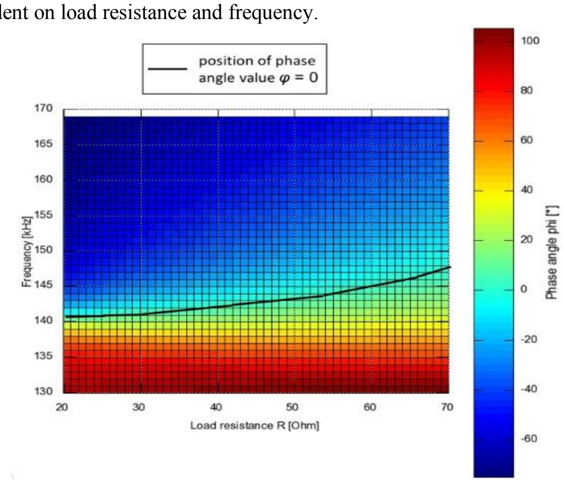

Fig. 6. Phase angle characteristic of a parallel-parallel compensated BIPT system dependent on load resistance and frequency.

Acknowledgement

The authors would like to thank the company POWERSYS for good cooperation concerning JMAG.

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