

A Dynamic Multivariable State-Space Model for Bidirectional Inductive Power Transfer Systems

Akshya K. Swain, *Member, IEEE*, Michael J. Neath, *Student Member, IEEE*,
Udaya K. Madawala, *Senior Member, IEEE*, and Duleepa J. Thrimawithana, *Member, IEEE*

Abstract—Bidirectional inductive power transfer (IPT) systems facilitate contactless power transfer between two sides, which are separated by an air gap, through weak magnetic coupling. Typical bidirectional IPT systems are essentially high-order resonant circuits and, therefore, difficult to both design and control without an accurate mathematical model, which is yet to be reported. This paper presents a dynamic model, which provides an accurate insight into the behavior of bidirectional IPT systems. The proposed state-space-based model is developed in a multivariable framework and mapped into frequency domain to compute the transfer function matrix of eight-order bidirectional IPT systems. The interaction between various control variables and degree of controllability of the system are analyzed from the relative gain array and singular values of the system. The validity of the proposed dynamic model is demonstrated by comparing the predicted behavior with that measured from a 1 kW prototype bidirectional IPT system under various operating conditions. Experimental results convincingly indicate that the proposed model accurately predicts the dynamical behavior of bidirectional IPT systems and can, therefore, be used as a valuable tool for transient analysis and optimum controller design.

Index Terms—Contactless power transfer, inductive power transfer, power converters, relative gain array, singular value analysis.

I. INTRODUCTION

INDUCTIVE power transfer (IPT) is becoming an accepted technology for supplying power to a variety of applications with no physical contacts. This technology transfers power from one system to another across an air gap and through weak magnetic coupling. It offers high efficiency typically between 85–90%, robustness, and high reliability, even when used in hostile environments, because it is unaffected by dust or chemicals. In the past, many unidirectional IPT systems, with various circuit topologies or compensation strategies and levels of sophistication in control, have been proposed and successfully implemented to cater to a wide spectrum of applications, ranging from very low-power biomedical implants to high-power battery charging systems [1]–[7]. Recently, bidirectional IPT systems have also been proposed and developed for applications such as V2G systems [8], [9].

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The authors are with the Department of Electrical and Computer Engineering, The University of Auckland, Auckland 1142, New Zealand (e-mail: a.swain@auckland.ac.nz).

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The power handling capability of IPT systems is usually improved through either series or parallel compensations [10]. As a consequence, these systems invariably become high-order resonant networks, which are complex in nature and difficult to both design and analyze, especially when operated at frequencies in the range of 10–50 kHz. Although the IPT technology has now established itself as a technique for contactless power transfer, both the design and analyses of such systems are still being carried out only through relatively simple steady-state models mainly because of their complex nature [11]–[17]. Steady-state models are incapable of providing an accurate insight into the dynamic behavior of the system and, as such, cannot be regarded as a tool that facilitates both proper controller synthesis and physical design, without which the system cannot be optimized. At present, therefore, there is a need for an accurate dynamic model, which can be used as a valuable tool during the design stage of any IPT system.

To address this need, this paper proposes a dynamic model for bidirectional IPT systems. The proposed model is based on the concept of state variables, and can easily be modified for unidirectional IPT systems. Using the model, the relative gain array (RGA) matrix is computed from the transfer function to investigate the interactions between various input–outputs of an eight-order parallel-compensated IPT system. Singular value analysis is also carried out to obtain information with regard to the degree of controllability of the system as such information is vital for controller design. Measured results, under various operation conditions of a 1 kW bidirectional IPT system, are compared with the predicted behavior to demonstrate that the proposed dynamic model is accurate and can be used as a valuable tool during controller synthesis and optimization of IPT systems.

This paper is organized as follows. Section II briefly describes the principle of bidirectional IPT system and develops a state variable model of the system. Behavior of the system from frequency domain information is studied in Section III A through RGA and singular value analysis. In Section IV, the dynamic model is validated by comparing its performance under various conditions using a prototype of a 1 kW bidirectional IPT system and Section V presents the conclusions.

II. DYNAMIC STATE VARIABLE MODEL OF A TYPICAL BIDIRECTIONAL IPT SYSTEM

The schematic of a typical bidirectional IPT system proposed in [8] is shown in Fig. 1. The output of the pick-up is connected to the load, which is represented as a dc supply to either absorb or deliver power. Analogous to typical IPT systems, a

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colleagues and former students gathered at a workshop held in Notre Dame Indiana This workshop brought together many people whose lives have been touched by Mike to celebrate his milestone 70th birthday and to congratulate him on his contributions in the fields of systems circuits and control Mike was born on March 22 1937 in St Louis Missouri After obtaining his B S E E and M S E E at St Louis University he went on to study at the University of Illinois at Urbana Champaign for his doctoral degree With his Ph D degree complete he came to the University of Notre Dame in 1965 as an assistant professor He became an associate professor in 1968 a full professor in 1972 and the Frank M Freimann Chair in Electrical Engineering in 1982 He has remained at and loved the University of Notre Dame for over 40 years Mike also held a number of consulting jobs throughout his career Most notably he consulted with the Energy Controls Division of Allied Bendix Aerospace from 1976 to 1988 and the North American Operations branch of the Research and Development Laboratory of General Motors Corporation for a decade 1984 1994

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