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Introduction

1.1 Background and Significance

Impedance, in electrical engineering, is a complex quantity that combines resistance and reactance to characterize the total opposition that a circuit or component presents to current flow [1]. This fundamental parameter exhibits distinct behavior under nonoperational (offline) and operational (online) conditions [2]. Offline impedance is measured when a device or system is powered off and is therefore unaffected by its actual operating state. In contrast, online impedance, also referred to as in-circuit impedance, is measured while the device or system is energized and interacting with the power source. As a result, online impedance provides real-time information that more accurately reflects the true electrical characteristics of the system under practical working conditions.

The significance of online impedance measurement spans a wide range of engineering domains, highlighting its essential role in improving reliability, efficiency, stability, and safety across diverse applications. In power electronics, online impedance measurement provides essential information for enhancing device reliability and operational efficiency, supporting system diagnostics and design improvements [3–5]. In the transportation sector, it facilitates condition monitoring of motor drive systems (MDS) [6–8], and plays a vital role in diagnosing and monitoring critical components in rail transit infrastructures, such as light rail transit (LRT) [9] and mass rapid transit (MRT) systems [10]. Moreover, online impedance information enables the systematic design of common-mode (CM) electromagnetic interference (EMI) filters for MDS [11], leading to more effective EMI suppression under real operating conditions. In power and energy systems, online impedance measurement is indispensable for the condition monitoring of critical assets such as batteries [12–14], power transformers [15], and high-power DC feeders [16]. Photovoltaic (PV) systems also benefit from online impedance measurement, which enhances their operational reliability [17, 18]. Furthermore, online impedance supports stability analysis of power electronic systems and grid-connected converters [19, 20], underscoring its expansive applicability and essential role in modern engineering.

Online impedance measurement can generally be implemented using three primary approaches: the voltage–current (V–I) approach, the capacitive coupling approach, and the inductive coupling approach [21]. The V–I approach determines the online impedance by measuring the voltage across and the current flowing through an energized system under test (SUT), followed by digital signal processing based on Ohm's Law [22–24]. The capacitive coupling approach employs coupling capacitors to block low-frequency or direct current (DC) power components while allowing high-frequency test signals to pass, enabling impedance extraction using an impedance analyzer (IA) or a vector network analyzer (VNA) [25–27]. However, both the V–I and capacitive coupling approaches require some form of direct electrical contact with the energized SUT, which increases implementation complexity and might introduce electrical safety risks in high-voltage and high-power environments. In contrast, the inductive coupling approach eliminates direct electrical contact with the energized SUT, thereby simplifying on-site implementation and enhancing safety [2]. Owing to its noncontact nature, it is also known as the electrically contactless online impedance measurement approach.

Based on the inductive coupling theory, a series of noncontact online impedance measurement setups has been developed to address different measurement requirements. These include the frequency-domain two-probe setup (FD-TPS) [28], time-domain two-probe setup (TD-TPS) [29], frequency-domain single-probe setup (FD-SPS) [30], and time-domain single-probe setup (TD-SPS) [31]. In addition, the frequency-domain three-probe setup (FD-THPS) [32] and time-domain multi-probe setup (TD-MPS) [33] have been developed to simultaneously measure the online impedances of SUTs across two or multiple branches powered by the same source. Despite being rooted in the inductive coupling approach, these setups exhibit respective characteristics in design theory, principle, and applicability. Each configuration is tailored to meet unique measurement challenges, offering solutions for time-variant measurements, multifrequency simultaneous measurements, varying measurement efficiency and complexity in implementation, etc. This array of noncontact measurement setups underscores the flexibility and adaptability of the inductive coupling approach, establishing it as a versatile and effective solution for contemporary challenges in online impedance measurement.

1.2 Organization of This Book

This book provides a comprehensive exploration of the theory, technological developments, and practical applications of electrically contactless online impedance measurement. It is designed to bridge the gap between traditional impedance measurement techniques and modern noncontact approaches, presenting both foundational principles and recent innovations that have shaped the field. The chapters are organized as follows:

This chapter discusses the evolution and importance of online impedance measurement, emphasizing the scope and significance of noncontact methods across diverse applications, preparing the reader for the detailed technical exploration to follow.

Chapter 2 presents a detailed comparison of three prevalent online impedance measurement approaches: the V–I approach, the capacitive coupling approach, and the inductive coupling approach. This chapter establishes a fundamental basis for understanding the advantages and limitations of each method, with particular emphasis on the benefits of inductive coupling for noncontact measurement.

Chapter 3 explores two main types of two-probe setups (i.e., FD-TPS and TD-TPS) based on inductive coupling, detailing the effects of probe-to-probe coupling and the calibration techniques used to mitigate these effects.

Chapter 4 analyzes two types of single-probe setups (i.e., FD-SPS and TD-SPS) utilizing the inductive coupling approach, covering their theoretical foundations, configurations, practical implementations, and necessary calibration procedures.

Chapter 5 elaborates on two types of complex multi-probe setups (i.e., FD-THPS and TD-MPS) and their different unique objectives compared to two-probe and single-probe setups.

Chapter 6 provides a detailed comparative analysis of single-probe, two-probe, and multi-probe setups, evaluating their advantages, limitations, and suitability for different application criteria, aiding readers in selecting an appropriate technology for specific needs.

Chapter 7 presents applications of noncontact online impedance measurement in power electronics, including EMI filter design for switched-mode power supplies, as well as health diagnosis and voltage-dependent parasitic capacitance extraction of power semiconductor devices.

Chapter 8 examines the use of noncontact online impedance measurement in transportation systems, including MDS, LRT, and MRT. This chapter focuses on their systematic CM EMI filter design, fault detection, and health monitoring, respectively.

Chapter 9 discusses applications in power and energy systems, such as transformer condition monitoring, defect detection in high-power DC feeders, and EMI estimation of PV systems. These examples demonstrate how noncontact techniques strengthen system reliability and maintenance strategies.

Chapter 10 concludes the book by summarizing key insights and projecting future research directions and technological advancements in noncontact online impedance measurement, suggesting paths forward for this evolving field.

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