



# Advances in Leakage Current Suppression for Dynamic Wireless Power Transfer System

Zizhu Tang

School of Advanced Technology, Xi'an Jiaotong-Liverpool University, Suzhou 215123, China  
Zizhu.Tang23@student.xjtlu.edu.cn

**Abstract.** This paper presents a systematic investigation into the research progress on leakage current suppression in N-leg inverters for dynamic wireless power transfer (DWPT) systems. With the widespread adoption of electric vehicles, DWPT technology has emerged as a critical solution due to its convenient and efficient charging capabilities. As a core transmitter-side topology, the N-legged inverter significantly enhances system scalability by reducing the number of switches from  $4n$  in conventional full-bridge inverters to  $4+2n$ . However, this architecture introduces new leakage current challenges stemming from voltage disparities in standby coils, leading to copper losses and electromagnetic interference (EMI) that compromise system efficiency and safety. Addressing these challenges, this study comprehensively reviews two predominant suppression strategies: the short-pulse control method and the pulse-width phase modulation method. After analyzing the limitations of these approaches, the paper proposes enhanced control strategies extended to n-leg configurations, emphasizing the critical importance of synchronizing all standby bridge arms in multi-vehicle charging scenarios to prevent additional power consumption and resonance issues caused by asynchronous operation. Ultimately, this research provides essential technical references and practical guidance for leakage current management, topology optimization, and efficient deployment in DWPT systems.

**Keywords:** Dynamic Wireless Power Transfer (DWPT) Systems, N-Legged Inverter, Leakage Current.

## 1 Introduction

Due to the significant air pollution caused by traditional fossil fuel vehicles and the rapid technological maturation of modern electric vehicles, numerous governments have implemented various policies to incentivize the purchase of electric vehicles, thereby increasing their market share. As a result, modern electric vehicles have emerged as an attractive transportation alternative to conventional automobiles [1]. However, the energy density of lithium-ion batteries, which are among the most competitive energy storage solutions (100-200 Wh/kg), remains significantly inferior to that of gasoline (12 kWh/kg) [2]. Consequently, the extensive deployment of charging infrastructure represents a more viable solution compared to the utilization of

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a substantial battery fleet. Dr. Covic et al. previously proposed the concept of Dynamic Wireless Power Transfer (DWPT), a hands-free charging system designed to eliminate interference from any external factors.

In current research, the transmitters of DWPT are primarily categorized into two major types: long transmitters and segmented transmitters [3]. This article mainly focuses on segmented transmitters. Segmented transmitters can solve problems such as magnetic field suppression, self-inductance of large transmitting coils, and difficulties in compensating for coil impedance that exist in long transmitters [4]. As the segmentation size of the coil decreases, it enables more precise control over magnetic leakage and exposure issues, as well as electromagnetic interference, thereby enhancing coupling efficiency and transmission performance. However, this approach significantly increases system complexity, particularly in large-scale coverage DWPT systems [5].

To address this issue, Dr. Farajizadeh employed the improved LCC compensator he introduced in another article and proposed an optimization outcome for the full-bridge inverter: the expandable N-legged converter (NLC) [6]. However, this enhancement has resulted in significant leakage current.

This novel topological architecture significantly reduces the required number of switching devices, decreasing from  $4n$  in full-bridge inverters to  $4+2n$  [7]. Notwithstanding the reduction in the number of switches, the proposed methodology concomitantly results in an  $n$ -fold increase in the maximum current stress imposed on each individual switch [8]. This power conversion topology utilizes  $n$  parallel-arranged half-bridge cells to achieve its N-leg configuration. Each Leg is equipped with two switches, namely a low-side switch and a high-side switch, collectively referred to as Arms. When at least one charging coil is in the charging state, leakage current flows within the uncoupled coils, resulting in copper losses and electromagnetic interference (EMI), which leads to energy wastage and a reduction in transmission efficiency [9]. In the research conducted by Dr. Takagi et al., a short-pulse switching method was proposed. This method involves synchronously activating the operational branch and the adjacent standby branch, followed by a rapid deactivation within a short period. This approach allows the charging current to flow through the switch rather than the coil, while the swift deactivation prevents the formation of an LC oscillatory circuit, thereby mitigating copper losses and electromagnetic interference.

In 2024, Dr. Takagi and his research team once again made a groundbreaking discovery, demonstrating that pulse control optimization can be achieved by modulating the Pulse-width ratio and phase offset of the standby leg Leg3, thereby effectively suppressing leakage current and precisely regulating electromagnetic field intensity. This innovative approach also presents a cost-effective and efficient solution for leakage current management in DWPT systems [10].

In light of the aforementioned issues, this paper will focus on investigating two potential solutions to address the leakage current problem induced by N-leg inverters in DWPT systems. The first section provides a concise overview of the two switching strategies proposed by Dr. Takagi and their efficacy in leakage current suppression. Building upon this foundation, the second section proposes an extension of his theoretical approach to multi-legged ( $n$ -legged) structural enhancements. The third

section examines the limitations of this study and suggests potential avenues for resolution. Finally, the paper concludes with a comprehensive summary of the relevant research.

## 2 Enhancements to Conventional Switching Methodologies

To address the limitations of short battery life in new energy electric vehicles and the high cost associated with traditional dynamic wireless charging inverter topologies, Dr. Farajizadeh proposed the concept of an n-leg inverter. In contrast to conventional full-bridge inverters, the n-leg inverter comprises n half-bridge units, offering superior scalability to accommodate dynamic wireless charging requirements over extended distances [3].

However, the innovation in this topology has also introduced new engineering challenges, particularly the emergence of leakage current. In the initial design, the author failed to adequately account for the current leakage issues arising from switching sequence discrepancies among half-bridge inverters, merely opting to deactivate both the upper and lower switching transistors of adjacent standby bridge arms during non-operational states. The full-off method, despite its straightforward logic, exhibits capacitive behavior during the turn-off process due to the voltage differential across the upper and lower switching transistors in the standby bridge arm. This charge-discharge process induces leakage currents in adjacent standby coils, consequently generating additional copper losses and electromagnetic interference (as illustrated in Fig. 1) [8].

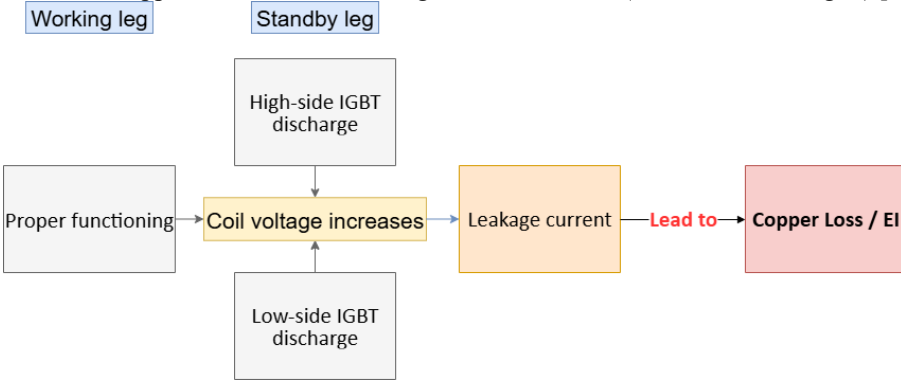


Fig. 1. Causes of leakage current. (Picture credit: Original)

To suppress such leakage currents, traditional methods mainly include two strategies. The first approach is the aforementioned full-off method, while the second is the synchronous method, which involves simultaneously activating the working bridge arm and the adjacent standby bridge arm. Synchronization methodology effectively mitigates leakage current; however, its synchronous switching characteristics tend to form resonant circuits (as documented in literature, such circuits are modulated into low-impedance paths), presenting significant challenges in practical engineering applications.

In addressing this issue, Dr. Takagi proposed two more sophisticated suppression strategies: the first is the duty cycle modulation method, which involves synchronizing the standby bridge arm with the active bridge arm for activation but promptly deactivating it at the moment of initiation; the second is the phase delay modulation method, which builds upon the former by introducing advanced or delayed control of switching sequences, thereby attenuating the formation of leakage currents through precise adjustment of the phase angle and duty cycle of adjacent standby legs [8] [10]. The two methodologies demonstrate superior performance in leakage current suppression compared to the synchronous approach (as detailed in Tables 1 and 2), while effectively mitigating resonance path issues.

However, in practical applications, the differences at the device level still need to be fully considered. Switching devices from various brands and materials exhibit distinct characteristics in terms of turn-on time, turn-off time, and capacitive properties, which imposes more stringent requirements on the implementation and optimization of the aforementioned modulation methodologies. Consequently, the selection and experimental validation of switching transistor types tailored to specific application scenarios remain indispensable engineering procedures.

**Table 1.** RMS Leakage Current – Conventional vs. SPST  
(Data from: simulation and experimental results in [8])

Method	Simulation (RMS)	Experiment (RMS)
Off	2.67 A	642.3 mA
Identical	388 mA	1.075 A
Puls	46 mA	62.4 mA

**Table 2.** EMF Comparison – Conventional vs. CCA.  
(Data from: experimental results in [10])

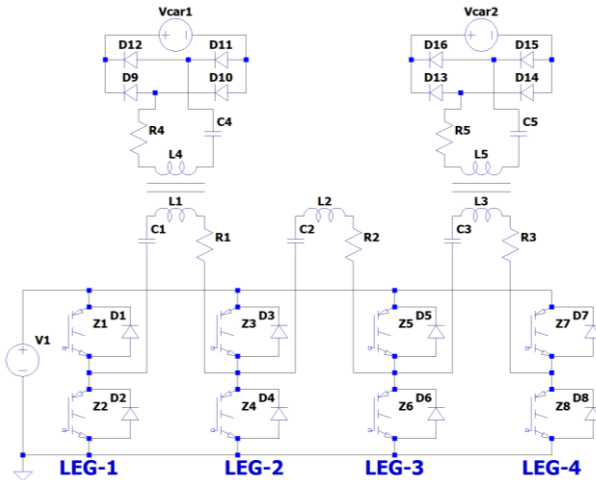
Method	Experiment
Ambient	0.235 $\mu$ T
Off	9.58 $\mu$ T
Identical	60.8 $\mu$ T
Pulse Width and Phase Adjustment $s_3 = 0.4, d_3 = 0.005$	0.304 $\mu$ T

### 3 Analysis and Discussion on the Extension from Three-Legged to n-Legged Configurations

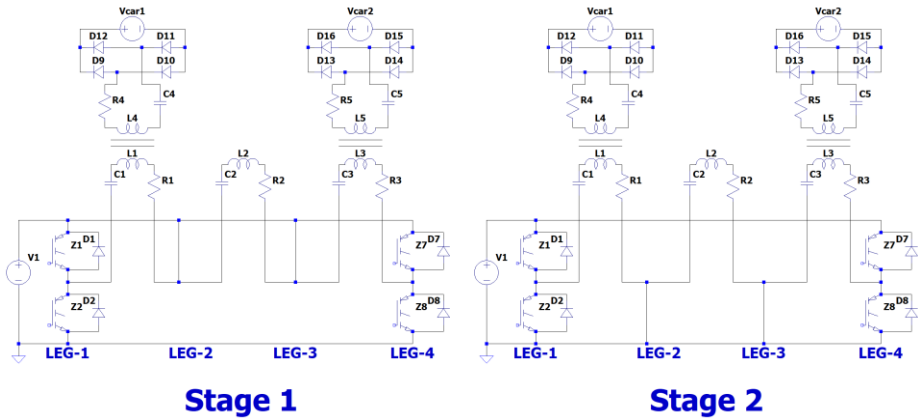
Both methodologies proposed by Dr. Takagi have been rigorously validated through simulation and experimental studies. However, these approaches are primarily based on sequence models established for three-leg inverters, and their practical applications in real-world scenarios remain to be further explored. This paper initially assumes that only one vehicle traverses this particular segment of the road. When a car passes through a coil, the coil will receive a signal to start, and the two working legs will switch with the adjacent standby legs in the method proposed by Dr. Takagi, which can reduce

the current generated on the adjacent standby coil to a certain extent, thereby suppressing copper loss and electromagnetic interference. However, due to the n-leg inverter configuration, standby legs are present on both sides of adjacent standby legs. In the fully off state, this configuration can induce leakage currents, while synchronization may also create resonant circuits. Therefore, this paper proposes synchronizing all standby legs with their adjacent counterparts, thereby simultaneously reducing leakage currents and preventing the formation of resonant circuits between standby legs.

Based on this foundation, when multiple trams traverse the same route simultaneously, this methodology can be employed to minimize energy loss. In scenarios where two vehicles operate close proximity, it suffices to maintain standard switching duty cycles and phase control for optimal operation. It is crucial to note that when two vehicles simultaneously enter the charging lane with a spacing exceeding one coil length (as illustrated in Fig. 2, assuming a four-leg inverter configuration), manual synchronization of the corresponding bridge arms should be implemented. Specifically, if the leading vehicle passes coil 3, activating bridge arms 3 and 4, while the following vehicle passes coil 1, activating bridge arms 1 and 2, asynchronous operation between bridge arms 2 and 3 would inadvertently activate coil 2. This scenario, if occurring during simultaneous charging of both vehicles, would result in power consumption equivalent to that of three vehicles. Similarly, when the interval between two vehicles exceeds one coil, asynchronous switching may induce corresponding conditions due to the interconnected nature of the coils. Therefore, it is advisable to delay the activation of the coil until the corresponding bridge arms can achieve synchronization (i.e., bridge arm 1 synchronizes with bridge arm 4, and bridge arm 2 synchronizes with bridge arm 3) after the rear vehicle enters the charging channel. The intermediate bridge arms should continue to be controlled using the synchronous modulation method.



**Fig. 2.** Illustrates a four-leg inverter configuration, where coils 1 and 2 are precisely positioned directly above individual electric vehicles, respectively. (Picture credit: Original)



**Fig. 3.** Illustrates the operational states of the switching transistors: Stage 1 corresponds to the simultaneous activation of transistors 2 and 4, while Stage 2 represents the concurrent activation of transistors 3 and 5. (Picture credit: Original)

It is noteworthy that the same approach in Dr. Takagi's study would result in a resonant circuit as illustrated in Fig. 3 [10]. However, the original text mentions that the dead time causes the voltage across the standby coil to become uncontrollable, thereby generating a voltage difference that induces current and consequently forms the resonant circuit. The methodology proposed in this study effectively prevents voltage instability. Specifically, it ensures that the voltage across the standby coil 2 remains equal, thereby eliminating any potential voltage difference. Consequently, this configuration precludes the generation of current, thus averting the occurrence of resonant circuits.

## 4 Conclusion

This paper provides a systematic review of research advancements in leakage current suppression for N-leg inverters in Dynamic WPT systems. The issue of leakage current is primarily induced by the voltage differential between bridge arms during dead-time intervals, which not only results in substantial copper losses and electromagnetic interference but also poses significant challenges to the overall system efficiency and operational safety. In addressing this issue, the paper provides a concise analysis of two representative suppression strategies currently in use: the short-pulse control method and the collaborative regulation approach. The implementation of both approaches effectively mitigates leakage current while preventing the generation of resonant circuits, thereby enhancing system stability and economic efficiency. This provides crucial technical support for the optimized deployment of wireless charging coils. Building upon this foundation, this paper proposes an enhanced methodology for extending the theoretical framework to the control of switching sequences in n-leg structures, thereby providing valuable insights for topology optimization and control strategy design in multi-vehicle simultaneous charging scenarios.

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