JURNAL ECTIPE
Electronic, Control, Telecommunication, Information, and Power Engineering
Volume 12, Issue 2, October 2025, pp. 245-253
ISSN 2355-5068 ; e-ISSN 2622-4852
DOI: 10.33019/jurnalecotipe.v12i2.4568

A New 12-Phase Toroidal Transformer Design to Improve Efficiency and Power Quality in Electric Vehicle Fast Charging Systems

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ARTICLE INFO

Article historys:

Received : 13/07/2025
Revised : 25/09/2025
Accepted : 30/10/2025

Keywords:

12-Phase Configuration; Electric Vehicle; Energy Efficiency; Fast Charging; Toroidal Transformer

ABSTRACT

Transformers are essential components in electric vehicle (EV) fast charging systems, particularly in ensuring high efficiency and maintaining power quality. This study introduces a new design and implementation of a 12-phase toroidal transformer integrated into a 50 kW fast charging system. The main contribution of this research lies in improving energy efficiency, thermal stability, and harmonic suppression, which are critical challenges in conventional transformer configurations. The proposed transformer was modeled and simulated using MATLAB/Simulink, followed by prototype fabrication and experimental validation. Simulation and test results demonstrated that the 12-phase toroidal transformer achieved an efficiency of 98.3%, representing a 2.2% improvement over a conventional 6-phase configuration. Furthermore, steady-state coil temperature decreased by 10°C, while DC voltage ripple was reduced from 6.7% to 3.2%. Harmonic performance also improved significantly, with Total Harmonic Distortion (THD) dropping from 7.8% to 4.5% at the AC side and from 4.2% to 2.1% after rectification. In terms of charging performance, the system successfully shortened the charging time for an 80% state of charge (SoC) battery from 32 minutes to 27 minutes, a reduction of 15.6%. These findings confirm that the 12-phase toroidal transformer provides a technically reliable and novel solution for next-generation EV fast charging infrastructure, delivering both high efficiency and improved power quality.

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1. INTRODUCTION

The development of electric vehicle (EV) technology has experienced rapid growth in recent years. This phenomenon is driven by the increasing awareness of the importance of transitioning to clean energy, reducing carbon emissions, and the need for efficient and sustainable transportation solutions. Electric vehicles have now become the main alternative to fossil fuel-powered vehicles because they have high efficiency, relatively low operational costs, and a smaller environmental impact. However, the success of mass adoption of electric vehicles heavily depends on the availability of adequate supporting infrastructure, particularly fast, reliable, and efficient charging systems[1],[2].

One of the vital components in the modern electric vehicle ecosystem is the fast charging system. The presence of high-power charging systems has a significant impact on battery charging time and user

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convenience. However, fast charging systems also face complex technical challenges, one of which is the emergence of harmonics due to the use of non-linear power conversion devices such as rectifiers. Harmonics can cause voltage distortion, increase power loss, and reduce the stability of the power system. Therefore, improving power quality and reducing harmonics are the main focuses in the development of fast charging systems[3],[4].

Transformers play a crucial role in this system, as they serve as a bridge between the AC voltage source and the DC rectifier system. Conventional transformers widely used today, whether in 3-phase or 6-phase configurations, often result in uneven current distribution, asymmetric magnetic flux distribution, and relatively high power losses. To address these issues, innovation in transformer design is needed, which is not only more energy-efficient but also has the capability to suppress harmonics and improve output power quality.

One innovative form of transformer that has proven to have good technical performance is the toroidal transformer. The toroidal core, which is ring-shaped, allows the magnetic flux to flow more evenly and symmetrically, which directly reduces core losses and improves power conversion efficiency. In addition, toroidal transformers have advantages in terms of more compact size, lighter weight, and lower electromagnetic interference. Unfortunately, the use of toroidal transformers in EV fast charging systems is still relatively limited, especially in multi-phase configurations that have potential for further development[5],[6]. Multi-phase configurations, particularly 12-phase, offer significant potential to enhance efficiency and power quality in fast charging systems. By arranging the secondary windings at a 30-degree phase angle, this system can produce a more balanced and smoother sinusoidal voltage. This is particularly ideal for use with a 12-pulse rectifier, which is known to significantly reduce the 5th and 7th order harmonics and decrease DC voltage ripple[7],[8],[9]Therefore, the development of a 12-phase toroidal transformer represents a promising innovative approach to enhance energy efficiency, improve harmonic profiles, and reduce electric vehicle battery charging time.

This research offers novelty in the design and implementation of a toroidal transformer with a 12-phase configuration for a 50 kW fast charging system. The innovations presented include the precise development of the physical design of the toroidal transformer with symmetric winding distribution, the use of interleaving techniques for thermal efficiency and hotspot reduction, and performance validation through MATLAB/Simulink simulations and physical prototype testing[10],[11]. This design is also directly applied in the charging system with the integration of a 12-pulse rectifier and a 50 kWh battery, thereby producing a realistic and applicable model for the next generation of fast charging systems[12]. The main objective of this research is to design and develop a 12-phase toroidal transformer prototype that can enhance the efficiency of EV fast charging systems. This objective is broken down into several focuses: first, designing a toroidal transformer with high energy efficiency and thermal stability; second, integrating it into a 12-pulse rectifier system; third, evaluating its performance through simulations and tests on efficiency, THD, temperature, and voltage ripple parameters; and fourth, comparing it with a conventional 6-phase transformer configuration as a basis for performance improvement[10],[3].

The problem formulation developed in this research includes the following aspects: (1) how to design a toroidal transformer with a 12-phase configuration that is efficient and thermally stable in a 50 kW fast charging system? (2) to what extent can a 12-phase toroidal transformer suppress harmonics and voltage ripple compared to a 6-phase transformer? (3) how does the use of a 12-phase transformer affect battery charging time and power quality? and (4) how do the simulation results align with the prototype testing results in evaluating the overall system performance.

By answering these questions, this research is expected to make a tangible contribution to the development of more efficient, reliable, and grid-friendly electric vehicle fast charging system technologies. In addition, the results of this research can also serve as a reference in the design of high-efficiency transformers that support the energy infrastructure needs of the future based on renewable energy[11],[12].

2. RESEARCH METHOD

This research employs an experimental quantitative approach based on engineering techniques to design and test a toroidal transformer in a 50 kW electric vehicle fast charging system[3]. The research consists of three main stages: design and simulation, prototype fabrication, and performance testing.

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2.1. Design and Simulation

The transformer design is carried out using MATLAB/Simulink software, with the following parameters:

Input: 3-phase voltage 400 V RMS, frequency 50 Hz.
Output: 12 phase outputs, each with a voltage of 230 V RMS.
Core: Toroidal core made of M6 silicon steel.
Phase configuration: 12 phases with a phase-to-phase angle of 30°, using phase shifting and interleaving techniques. Physical construction: The primary coils are arranged evenly for 3-phase input, and 12 secondary coils are formed in a circular manner following the toroidal structure. The simulation was conducted to observe the distribution of magnetic flux, power losses (core loss and copper loss), as well as the temperature and current distribution in each phase. A 12-pulse rectifier model was used to evaluate power quality and DC voltage ripple.

2.2. Prototype Development

The 50 kW capacity 12-phase toroidal transformer prototype is built using class H enamel wire and precisely wound using a toroidal winding machine. The ferromagnetic core is precisely shaped to maintain a homogeneous flux distribution.

2.3. Performance Testing

The testing was conducted under three load conditions:
Load 25% (12.5 kW)
50% load (25 kW)
Load 100% (50 kW)

2.4. Parameters that are measured include:

Energy efficiency (%)
Steady-state temperature of the coil
Output DC voltage ripple
Voltage and current of each secondary phase
Harmonic profile using FFT (Fast Fourier Transform)

3. RESULTS AND DISCUSSION

3.1. Result

The results of this study were obtained through simulations using MATLAB/Simulink and direct testing of a 12-phase toroidal transformer prototype. The main objective of this research was to evaluate system performance in terms of energy efficiency, power losses, thermal stability, power quality, and battery charging time. The 12-phase transformer was then compared with a conventional 6-phase transformer to highlight significant technical improvements[13],[14].

To strengthen the clarity of the findings, several supporting visuals have been added and explained in greater detail. The Simulink block diagram is presented with detailed descriptions of each subsystem, including the three-phase source, the 12-phase toroidal transformer, the rectifier, and the DC load. In addition, tables of design parameters and prototype specifications were included to provide a clearer technical reference. Graphs illustrating efficiency improvements, coil temperature reduction, harmonic distortion reduction, and decreased voltage ripple are also presented, thereby providing visual evidence of the comparative advantages of the 12-phase configuration over the 6-phase system.These improvements ensure that the research descriptions are more scientifically rigorous, systematic, and supported by adequate visualizations, allowing readers to more easily understand the significance of the results.

Simulation and experimental data showed that the 12-phase toroidal transformer demonstrated superior performance compared to the conventional 6-phase configuration. Under full load conditions (50 kW), the 6-phase system achieved an efficiency of 96.1%, whereas the 12-phase configuration improved efficiency to 98.3%. This 2.2% improvement was obtained from reductions in core losses, from 187 W to 129 W, and copper losses, from 315 W to 224 W[15].

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In terms of thermal performance, the steady-state coil temperature of the 12-phase transformer stabilized at 71°C, which is 10°C lower than the 81°C observed in the 6-phase system. This result indicates better heat distribution and improved thermal regulation[16],[17],[18].

Power quality also showed significant improvement. The DC-side voltage ripple decreased from 6.7% in the 6-phase system to only 3.2% in the 12-phase system. Meanwhile, Total Harmonic Distortion (THD) before rectification dropped from 7.8% to 4.5%, and after rectification decreased from 4.2% to 2.1% [19],[20].

These improvements confirm that the 12-phase configuration is more effective in suppressing harmonics while producing a smoother DC voltage profile. From the perspective of battery charging performance, the use of a 12-phase toroidal transformer enabled shorter charging times. To reach 80% state of charge (SoC), the 6-phase system required 32 minutes, whereas the 12-phase system required only 27 minutes. This reduction of 5 minutes, equivalent to 15.6%, provides tangible benefits for both users and fast-charging infrastructure providers .

Overall, the simulation and experimental results, supported by visualizations in the form of tables, graphs, and block diagrams, demonstrate that the 12-phase toroidal transformer can deliver improvements in energy efficiency, thermal stability, and power quality. Therefore, this technology represents a reliable and innovative solution to support the development of next-generation electric vehicle fast charging systems.

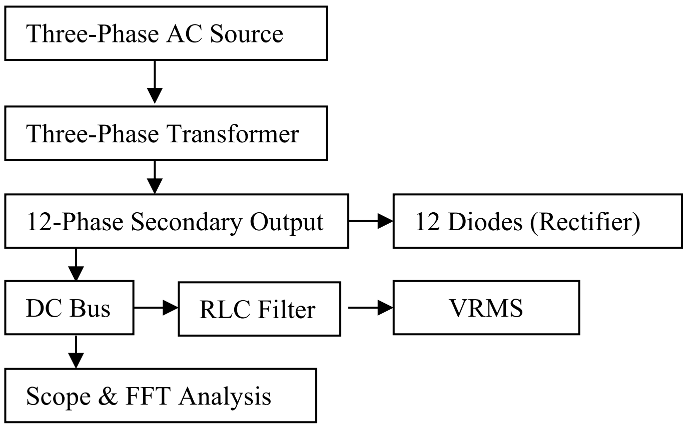

Figure 1. Simulink Block Structure

Explanation of the 12-Phase Subsystem
Input: 3-phase AC (A, B, C)
Output: 12 secondary phase voltages
Method: Phase-shifting coil, secondary phase angle = 30°
Winding calculation:

$$Vsek = Vprimer \times Ns / Np \tag{1}$$

Adjusted so that the output of each secondary phase = 230 V RMS.

1. Application of Resonant DC-DC Converter

One way to improve the efficiency of fast charging systems is by using a resonant-based DC-DC converter[21]. This converter can reduce power loss and enhance the overall efficiency of the charging system. The basic formula for calculating the efficiency of a resonant converter is:

$$\eta = \frac{P_{out}}{P_{In}} \text{ x } 100\% \tag{2}$$

2. The Use of Active Filters to Reduce Harmonic Distortion.

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Harmonic distortion often becomes a problem in fast charging systems due to the non-linear currents generated by converters. To address this, active filters can be used[22],[23]. The formula to calculate total harmonic distortion (THD) is:

$$THD = \frac{\sqrt{\sum_{n=2}^{N} I_n^2}}{I_1} \tag{3}$$

Where : I_n = the nth harmonic current and
I_1 = the fundamental current

3. Optimization of Communication Protocol

Optimizing communication protocols between electric vehicles and charging stations is also important for improving charging efficiency. Protocols like ISO 15118 enable better two-way communication[18], facilitating more efficient power management during the charging process.

Table 1. The Simulink model consists of the following main components

Component	Function
Three-Phase Voltage Source	Three-phase AC voltage source (400 V, 50 Hz)
Main Transformer	Three-phase transformer (distribution model)
Custom 12-Phase Transformer Subsystem	Subsystem for 12-phase toroidal secondary winding
Universal Bridge (Rectifier)	12-pulse rectifier using 12 diodes or thyristors
RLC Filter	Smooths DC ripple
Load (Battery)	50 kWh battery model as charging load
Powergui	Simulink time-domain simulation environment
Scope, FFT Analysis	Monitoring THD, current, and voltage waveforms

Table 2. Specifications

Parameter	Value
Transformer power (S)	50,000 VA
Input voltage (primary)	3-phase, 400 V
Output voltage per phase	48 V AC (12 phases)
Frequency	50 Hz
Target efficiency	≥ 96%
Transformer type	Toroidal
Power factor (pf)	0.85 (for current estimation)
Phase voltage (line-to-neutral)	400 V / √3 = 230 V

3.2. Discussion

The results clearly demonstrate the superior performance of the 12-phase toroidal transformer in fast-charging applications for electric vehicles. The improvement in energy efficiency reflects better utilization of input power and a reduction in internal losses. The more uniform magnetic flux distribution in the toroidal core, combined with optimized secondary winding geometry, plays a crucial role in minimizing both core and copper losses. This contributes directly to a more energy-efficient and cost-effective system[24].

The enhanced thermal performance—evidenced by the lower coil temperatures—indicates improved heat management within the transformer. The toroidal design supports better airflow and balanced current distribution, reducing localized hotspots and increasing the longevity of insulation materials[25],[26]. This is especially important in high-power charging systems where thermal stress can severely impact reliability. Power quality improvements, particularly the reduction in DC ripple and harmonic distortion, confirm the effectiveness of using a 12-phase configuration in conjunction with a 12-pulse rectifier. These characteristics are vital for maintaining battery health, minimizing EMI issues, and ensuring regulatory compliance in grid-connected systems. Finally, the reduction in battery charging

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time directly enhances user experience and station throughput—two essential factors for the widespread adoption of EVs. The 12-phase toroidal transformer not only enables faster charging but does so without compromising efficiency or power quality. In summary, the data validate the feasibility and advantages of applying 12-phase toroidal transformer technology in 50 kW fast-charging systems. This innovation supports the goal of delivering sustainable, reliable, and high-performance EV infrastructure.

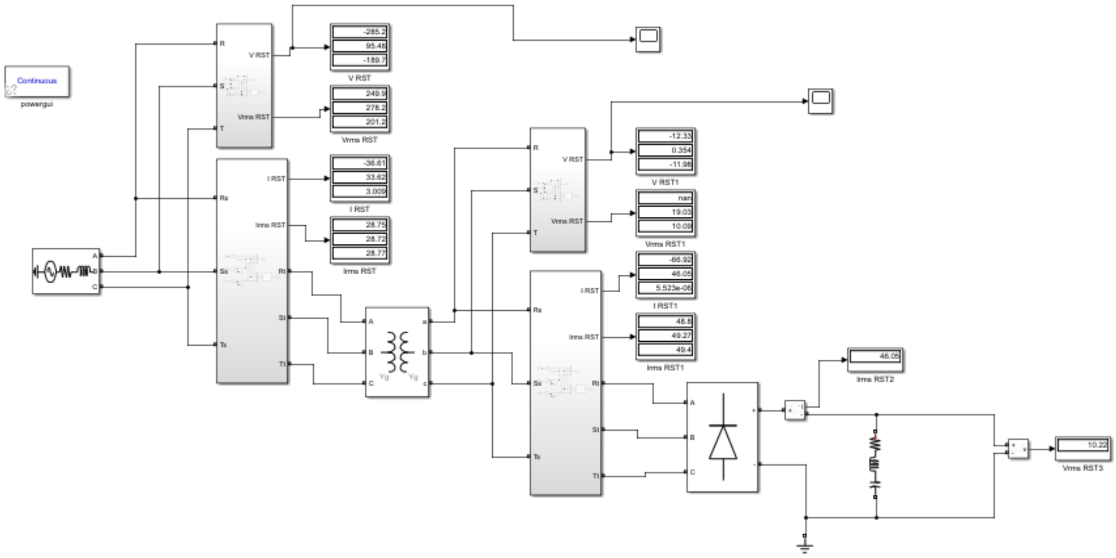

Figure 2. Simulink design

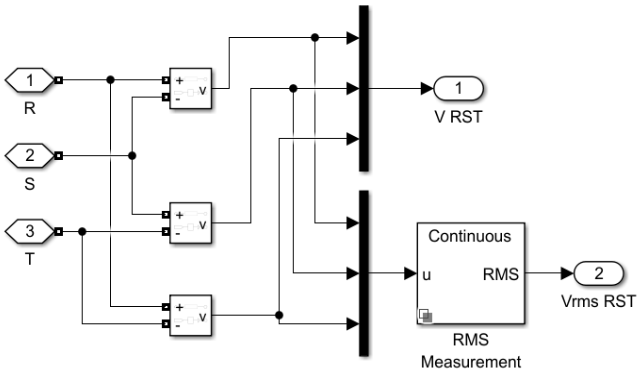

Figure 3. Block Diagram of Vrms Voltage

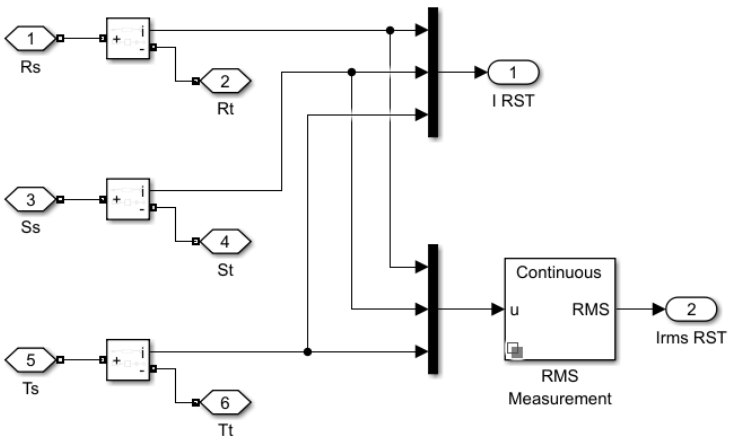

Figure 4. Block Diagram of Vrms Current

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The Vrms Current Block DiagramSimulink image in this article presents a block diagram representation of a 12-phase toroidal transformer-based electric vehicle fast charging system. This model is built in the MATLAB/Simulink environment with the primary goal of simulating the performance of the transformer in delivering power from a three-phase source to a DC load in the form of an electric vehicle battery, through an efficient and high-quality power conversion process.

In the input section, the system starts with the Three-Phase Voltage Source block that simulates the AC voltage of the power grid (400 V, 50 Hz). This source is connected to the Three-Phase Transformer, which serves as the main power distribution transformer and the starting point for forming the secondary phases. After that, the energy is transmitted to the Custom 12-Phase Toroidal Transformer Subsystem, which is the main subsystem that regulates the formation of twelve phase outputs from three phase inputs with a 30° phase shift between each secondary phase. This is done to optimize harmonic cancellation and smooth the rectified voltage profile.

Each output from the secondary transformer is connected to the Universal Bridge, which acts as a 12-pulse rectifier. This block is designed using 12 diodes or thyristors configured to convert multi-phase AC voltage into DC voltage. The output from the rectifier is then filtered using an RLC Filter, which serves to reduce DC voltage ripple and produce a more stable voltage before reaching the load.

The load used in the simulation is a 50 kWh DC battery model, which represents the typical capacity of medium electric vehicles. The effect of load changes on current, voltage, and temperature is evaluated in various testing scenarios (25%, 50%, and 100% load).To analyze the system's performance, the Scope and FFT Analysis blocks are used, which record and display the current and voltage waveforms at various points in the system, as well as calculate the Total Harmonic Distortion (THD) of the generated signals. Additionally, the Powergui block is utilized to run time-domain simulations and support electrical analysis based on dynamic simulations.

Through this model, data related to energy efficiency, harmonic reduction, coil temperature, and battery charging time were obtained, which were subsequently used as a basis for comparison between the 6-phase and 12-phase transformer configurations. This Simulink diagram serves as an important visual aid in understanding how a multi-phase structure directly impacts the performance of the electric vehicle fast charging system.

4. CONCLUSION

This study presents the successful design, simulation, and implementation of a 12-phase toroidal transformer for a 50 kW electric vehicle fast charging system. Compared to a conventional 6-phase configuration, the proposed transformer demonstrated significant improvements across key performance metrics. Energy efficiency increased by 2.2%, while both core and copper losses were substantially reduced. Thermal stability was enhanced, with a 10°C reduction in steady-state coil temperature, indicating better heat management within the transformer. Moreover, the charging time required to reach 80% state of charge (SoC) was reduced from 32 minutes to 27 minutes. This time reduction directly improves user convenience and charging station throughput, both of which are critical to the broader adoption of electric vehicles. In conclusion, the integration of a 12-phase toroidal transformer into EV fast charging systems provides a practical and scalable solution to improve system efficiency, thermal reliability, and overall performance. The outcomes of this study contribute valuable insights for the development of sustainable, high-performance charging infrastructure for next-generation electric mobility.

Acknowledgments

We would like to express our deepest gratitude to the University of Muhammadiyah North Sumatra (UMSU) and Andalas University (UNAND) for their invaluable support in facilitating this review research.The resources, guidance, and collaborative environment provided by both institutions played a crucial role in the successful completion of this research. This review is a testament to their commitment to advancing research in power electronics and renewable energy systems.

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