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PERFORMANCE ANALYSIS OF DC CHARGING TOPOLOGIES FOR ELECTRIC VEHICLES USING SIMULINK

Mohd. Abdul Muqeet[1*], Arshad Mohammed[2], G. Sailaja[3], G. Prasanna Kumar[4]

[*1,2] Electrical Engineering Department, Muffakham Jah College of Engineering and Technology, Hyderabad, India.
[3,4] Mechanical Engineering Department, Muffakham Jah College of Engineering and Technology, Hyderabad, India.
[1*]ab.muqeet2013@gmail.com (Corresponding author),
[2]arshad.mohammed@mjcollege.ac.in, [3]sailajasinha@mjcollege.ac.in,
[4]gprasanna@mjcollege.ac.in

Abstract: The growing adoption of electric vehicles (Electric Vehicles) necessitates robust and efficient DC charging infrastructure to address key challenges such as range anxiety and prolonged charging times. This study focuses on analyzing and implementing four DC charging topologies using Simulink: the SCR-based full-bridge rectifier, twelve-pulse diode bridge rectifier, six-pulse thyristor bridge rectifier, and twelve-pulse diode bridge rectifier with a three-level buck converter. Each topology was evaluated for performance, efficiency, and compatibility with constant current and constant voltage charging profiles. Simulation results demonstrated trade-offs between power factor, harmonic content, and system complexity. While advanced topologies like the three-level buck converter excelled in efficiency and power quality, simpler configurations offered cost-effective solutions for medium-power applications. The findings highlight the importance of topology selection based on specific application requirements, providing valuable insights for designing scalable and efficient Electric Vehicle charging systems.

1. Introduction

The alarming increase in carbon emissions has become a pressing issue for governments around the globe, with its far-reaching implications for climate change, public health, and environmental sustainability. This growing concern has driven policymakers to explore innovative solutions to mitigate carbon footprints and transition toward greener alternatives. Among the primary contributors to CO_2 emissions, internal combustion (IC) engine vehicles play a dominant role due to their reliance on fossil fuels and inefficient energy use. These vehicles emit significant amounts of greenhouse gases and other pollutants, exacerbating air quality issues and accelerating global warming. Electric vehicles present a transformative opportunity to address these challenges by offering an eco-friendly alternative to IC engine vehicles. Electric vehicles generate no emissions, helping to improve air quality, lower greenhouse gas levels, and reduce their overall environmental impact. Moreover, the escalating global oil prices make the operational costs of ICElectric Vehicles increasingly unsustainable, thereby strengthening the economic case for Electric Vehicle adoption. However, the widespread integration of Electric Vehicles hinges on the establishment of robust charging infrastructure, especially in emerging economies like India, where the adoption of Electric Vehicles is critical to reducing urban pollution and achieving energy security. Developing a fast-charging infrastructure has become a cornerstone for promoting Electric Vehicle adoption.

For electric vehicles to be widely accepted, it is imperative to resolve key consumer pain points, such as limited driving range and prolonged charging times. These concerns, often referred to as "range anxiety" and "charging convenience," play a pivotal role in shaping consumer perceptions of Electric Vehicle usability [1], [2], [3]. Addressing these issues through innovative technological advancements and strategic infrastructure planning can significantly enhance the appeal of Electric Vehicles among potential buyers. A typical Electric Vehicle charging infrastructure is composed of three essential systems: the operating system, which manages the overall functioning of the charging network; the customer information system, which provides real-time updates and user-friendly interfaces; and the charging system, which facilitates the transfer of energy to the Electric Vehicle battery [4]. Among these components, the charging system stands out as the most critical since it directly interfaces with the battery and determines the efficiency and reliability of the charging process. Depending on the power they deliver, charging systems are categorized as slow chargers or fast chargers [6-8].

Slow chargers, which generally handle a power range of 3–4 kW, are designed for overnight charging scenarios and are typically connected to standard household grids. While slow chargers offer a cost-effective and accessible solution for residential charging, their extended charging times—approximately 6–7 hours—limit their applicability for scenarios requiring quick energy replenishment. Conversely, fast chargers, capable of delivering around 50 kW of power, can recharge an Electric Vehicle battery in under an hour, making them ideal for commercial and high-demand applications. Modern Electric Vehicles are often equipped with advanced battery technologies optimized for high charge currents, underscoring the necessity of fast-charging infrastructure to meet user expectations. The integration of Electric Vehicles into power grids presents both opportunities and challenges. Some studies argue that the gradual adoption of Electric Vehicles is unlikely to strain the overall grid, particularly in large, well-balanced systems. However, localized circuits with lower grid inertia and resilience may face significant challenges [9-11]. Fast charging, in particular, demands substantial power—approximately 50 kVA per vehicle—comparable to the capacity of transformers in low-voltage distribution systems. This high-power demand necessitates careful planning and upgrading of grid infrastructure to prevent issues such as overloading and overcurrent-induced faults. Installing dedicated transformers for fast-charging stations in medium-voltage lines may alleviate some concerns, but heavily loaded feeders remain vulnerable to faults, especially under peak demand scenarios [12-16]. Fast chargers are predominantly installed in public spaces, including parking lots, shopping centers, and fuel stations, to provide convenient access for Electric Vehicle users. However, the deployment of fast chargers introduces a set of power quality issues due to the non-linear devices within these systems. These issues, which include voltage harmonics, current harmonics, and poor power quality, become more pronounced as Electric Vehicle adoption rates increase [1], [5], [8], [9]. Low power factors further exacerbate the situation, potentially leading to inefficiencies and increased operational costs. To address these concerns, power factor correction technologies can be employed, ensuring optimal energy efficiency and grid stability [2-4]. To foster confidence in Electric Vehicle adoption, it is essential to provide reliable home charging options, enable long-distance travel, and effectively address range anxiety. Public charging infrastructure, particularly direct current fast charging (DCFC), plays a pivotal role in achieving these goals. DCFC systems typically deliver 50 kW or more of power, enabling rapid battery replenishment by adding approximately 50 miles of range within 20 minutes [5], [8], [13]. Such advancements make Electric Vehicles more comparable to traditional gasoline vehicles in terms of convenience and usability. Researchers are also exploring ultra-fast charging technologies to further minimize refueling times and improve the user experience. Fast charging represents a critical technological milestone in the Electric Vehicle sector, addressing one of the most significant barriers to widespread Electric Vehicle adoption [16]. This paper is organized as follows: Section II delves into various charging methods, offering an in-depth analysis of their operational mechanisms and use cases. Section III explores different charging topologies, highlighting their design principles and practical implications. In Section IV, the implementation and simulation of these charging topologies are demonstrated using Simulink, accompanied by a discussion on the integration of Proportional-Integral-Derivative control blocks for enhanced system performance. Finally, the paper concludes in Section V, summarizing the findings and offering insights for future research directions

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2. Background theory

DC batteries demand regular and consistent charging to maintain their functionality and efficiency. In this context, we begin by outlining various charging methods and then delve into a detailed exploration of different DC charging topologies. These topologies play a pivotal role in ensuring efficient energy transfer and adaptability across various applications. The DC charging process is typically structured into two distinct stages:

a. AC to DC Converter Stage (Rectifier):

This stage is responsible for converting alternating current (AC) from the power grid into direct current (DC) suitable for charging the battery. The rectifier stage employs semiconductor devices such as diodes or thyristors to achieve this conversion efficiently. It plays a critical role in ensuring that the input AC power, which often fluctuates in voltage and frequency, is transformed into a steady DC output. Advanced rectifiers are designed to minimize power losses, improve conversion efficiency, and mitigate issues like harmonics and voltage instability.

b. DC to DC Converter Stage (Chopper):

Once the AC power has been rectified into DC, the next stage involves regulating and adapting the DC voltage and current to meet the specific requirements of the battery. This is achieved through a DC to DC converter, commonly referred to as a chopper. The chopper adjusts the output voltage and current based on the battery's charging profile, ensuring optimal charging speed while preventing overcharging or thermal stress. Modern choppers are equipped with advanced control mechanisms to enhance precision, efficiency, and safety during the charging process.

These two stages collectively form the foundation of DC charging systems, ensuring compatibility with diverse power sources and battery technologies. In addition, the choice of topology—such as buck, boost, or buck-boost converters—can be tailored to address specific requirements, including fast charging capabilities, high power efficiency, or compact design. Moreover, advancements in charging technology, such as bidirectional AC/DC converters, are enabling innovative applications like vehicle-to-grid (V2G) systems. These systems allow

Electric Vehicle batteries to supply power back to the grid during peak demand periods, further enhancing the utility of DC charging infrastructure. Similarly, incorporating intelligent control systems and real-time monitoring into DC chargers is helping optimize performance, reduce energy losses, and improve the overall user experience.

The integration of sophisticated DC charging topologies is essential to meet the evolving demands of modern battery systems. By ensuring seamless conversion and regulation of power, these technologies not only enhance charging efficiency but also pave the way for sustainable energy solutions in the context of electric mobility and renewable energy integration. The different charging methods are explained below.

I. Constant Voltage Charging

In constant voltage charging, a fixed voltage is applied across the battery terminals. Initially, the current is high but decreases as the battery charges, eventually tapering off. This simple, cost-effective method is widely used for lead-acid batteries in automotive and backup systems, requiring monitoring to prevent overcharging [7].

II. Constant Current Charging

In constant current charging, a fixed current is supplied regardless of voltage variations. As the battery charges, its voltage gradually rises. Charging stops when the full charge voltage is reached, preventing overcharging and ensuring efficiency [7]. This method, requiring voltage monitoring, is ideal for industrial applications demanding precision and safety.

III. Pulse Charging

Pulse charging applies controlled current pulses to the battery, with adjustable magnitude, frequency, and duration to optimize charging [10], [11]. Rest periods between pulses allow electrochemical stabilization, preventing imbalances. This method mitigates gas formation, crystal growth, and passivation, extending battery life. It is ideal for advanced systems requiring efficiency and longevity [13].

IV. Negative Pulse Charging

Negative pulse charging, a variation of pulse charging, enhances stabilization and efficiency by applying short discharge pulses during rest periods [13]. These pulses, two to three times the charging current, break gas bubbles on electrodes, preventing passivation. This method benefits gas-prone batteries, improving electrochemical balance, longevity, and overall charging performance.

A DC fast charger typically operates through two fundamental stages: the AC to DC conversion stage (Rectifier) and the DC to DC conversion stage (Chopper). These stages work together to efficiently transform AC power from the grid into regulated DC power suitable for charging electric vehicle (Electric Vehicle) batteries. This paper focuses on analyzing and implementing four widely recognized charging topologies using Simulink software. Each topology is explored in detail, including its design, simulation settings, and performance analysis. The following are the four common charging topologies discussed in [13]:

1. Silicon Controlled Rectifier-Based Full-Bridge Controlled Rectifier (Topology-I)

This topology utilizes a silicon-controlled rectifier (Silicon Controlled Rectifier)-based full-bridge configuration for AC to DC conversion. Silicon Controlled Rectifiers offer precise control over the rectification process by allowing phase-angle adjustment, enabling better regulation of the output voltage. This topology is especially advantageous in applications where the input voltage fluctuates or precise control of the output is required. Figure 1 illustrates the schematic diagram of this topology, showcasing the arrangement of the Silicon Controlled Rectifier-based rectifier and its integration with the transformer and battery charging system [13].

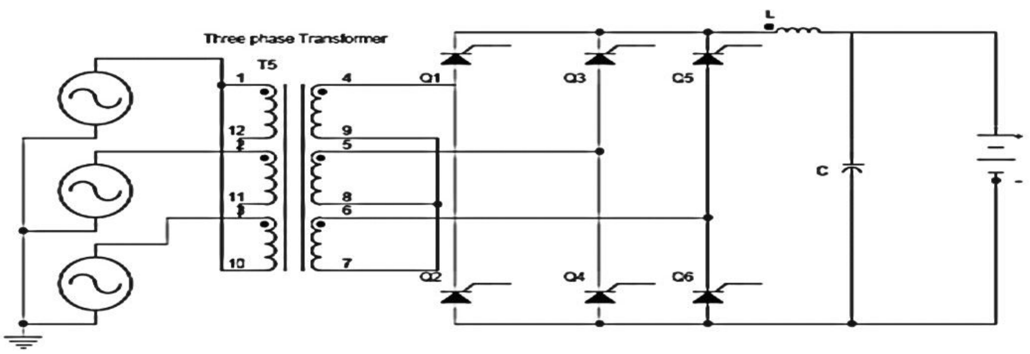


Figure.1: SCR based full-bridge controlled rectifier [13]

2. Twelve-Pulse Diode Bridge Rectifier Followed by Full-Bridge DC–DC Converter (Topology-II)

In this configuration, a twelve-pulse diode bridge rectifier is used for the AC to DC conversion stage. The twelve-pulse design helps reduce harmonic distortion in the input current, improving power quality. The rectified output is then fed into a full-bridge DC–DC converter, which provides efficient voltage regulation and ensures compatibility with the Electric Vehicle battery's charging profile. This topology is well-suited for applications requiring high power and low harmonic distortion.

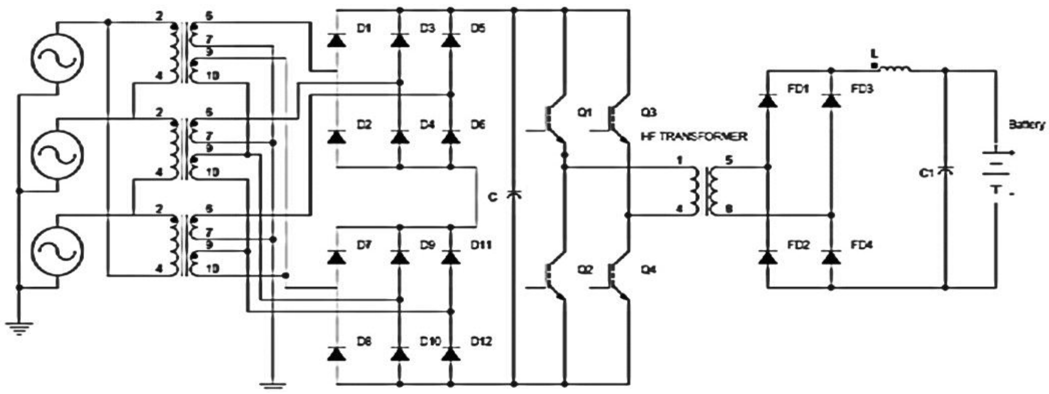


Figure 2. Twelve pulse diode bridge rectifiers followed by a full-bridge DC- DC converter [13]

3. Six-Pulse Thyristor Bridge Rectifier Followed by Full-Bridge DC–DC Converter (Topology-III)

This topology features a six-pulse thyristor bridge rectifier for the AC to DC conversion stage. Thyristors allow for controlled rectification by adjusting the firing angle, which provides flexibility in handling varying load conditions. The subsequent full-bridge DC–DC converter ensures stable and efficient voltage output. This configuration strikes a balance between performance and complexity, making it a versatile choice for medium-power applications.

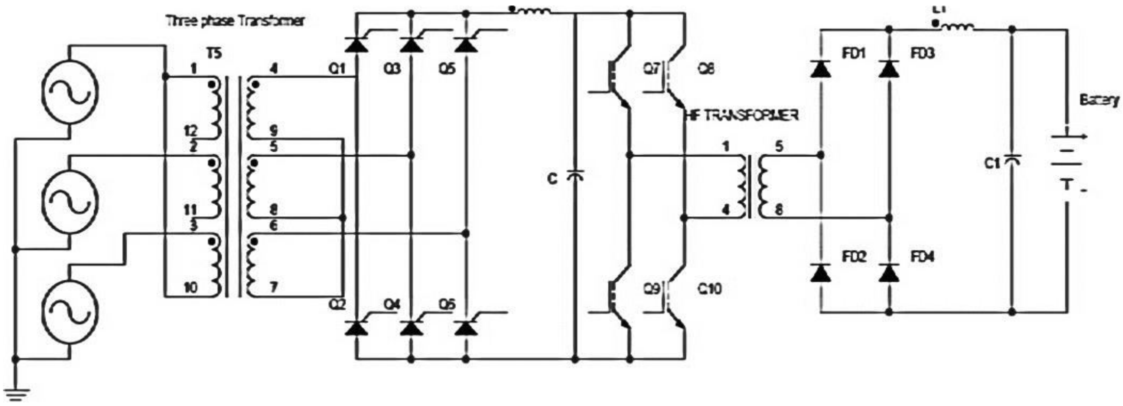


Figure 3: Six pulse thyristor bridge rectifier followed by a full-bridge DC-DC converter [13]

4. **Twelve-Pulse Diode Bridge Rectifier Followed by Midpoint Clamped Three-Level Buck Converter (Topology-IV)**

This advanced topology combines a twelve-pulse diode bridge rectifier with a midpoint-clamped three-level buck converter for the DC–DC stage. The three-level buck converter enables finer control over the output voltage and reduces voltage stress on the components, resulting in higher efficiency and reliability. This topology is particularly beneficial for high-power applications where efficiency and reduced switching losses are critical.

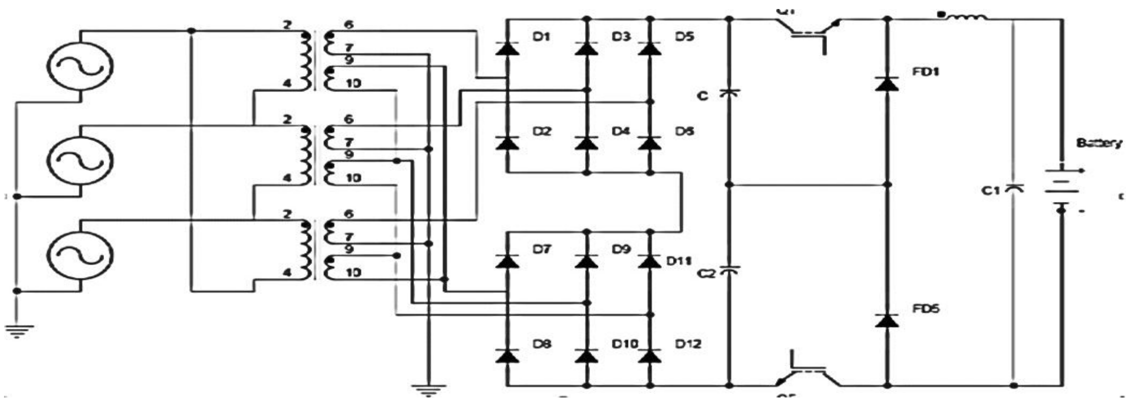


Figure 4: Twelve pulse diode bridge rectifier followed by midpoint clamped three-level buck converter [13]

3. **Experimental Results**

The Simulink models for the discussed topologies have been developed to analyze their performance under various charging conditions, ensuring compatibility with the constant current (Constant Current) and constant voltage (Constant Voltage) charging profiles required by Electric Vehicle batteries. The models are configured to simulate real-world operating scenarios and include essential components such as rectifiers, DC–DC converters, Proportional-Integral-Derivative controllers, and pulse generation mechanisms. Below is a detailed discussion of the implementation and results for each topology:

A. Silicon Controlled Rectifier-Based Full-Bridge Controlled Rectifier (Topology-I)

The Simulink model for this topology has been designed and implemented, as depicted in Figure 5. To enable closed-loop operation, a Proportional-Integral-Derivative (Proportional-Integral-Derivative) control mechanism has been incorporated into the simulation model, as illustrated in Figure 6. The charging system is configured to maintain a battery voltage of 56 V, with the current loop ensuring a maximum charging current of 80 A. The system dynamically adjusts the duty cycle of two insulated-gate bipolar transistors (IGBTs) based on the battery's charging requirements. If the battery voltage is below 56 V, the system allows the maximum charging current of 80 A to flow, ensuring rapid charging during the initial phase. As the battery voltage approaches 56 V, the charging current begins to taper off. This reduction in current is achieved by decreasing the duty cycle of the IGBTs, ensuring a smooth transition to the constant voltage phase and preventing overcharging. This closed-loop control ensures the battery is charged efficiently and safely, maintaining optimal conditions throughout the charging process.

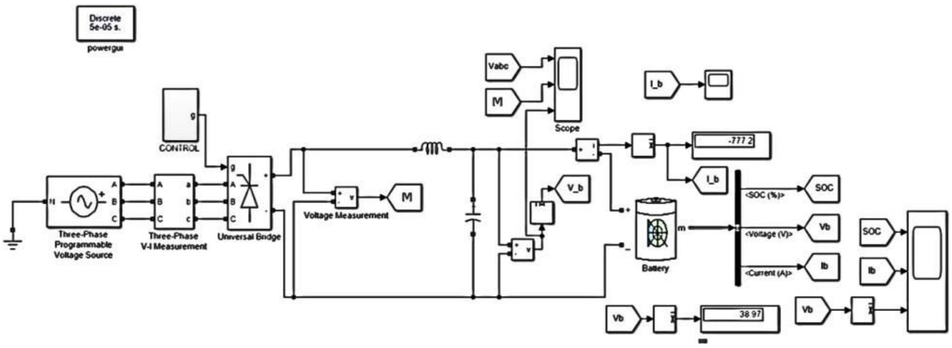
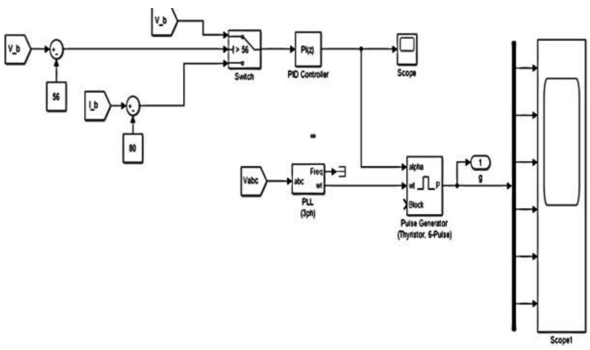


Figure 5: Simulink model for SCR based full-bridge controlled rectifier

The Pulse generator is used to provide Thyristor 6 pulses and act input to the universal bridge as shown in Fig. 7.



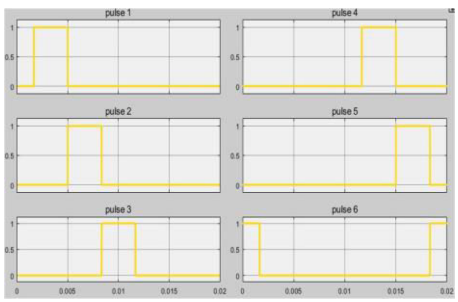


Figure 6: Simulink PID controlling model

Figure 7: Thyristor Six Pulses

The input voltages and rectified output are illustrated in Figure. 8. Simulink results in Figure. 9 indicate a battery current ripple exceeding 3% and a low input power factor. Additionally, the pulse charging scheme is incompatible with this topology, as the Silicon Controlled Rectifier continues conducting until the AC input signal reaches zero crossing.

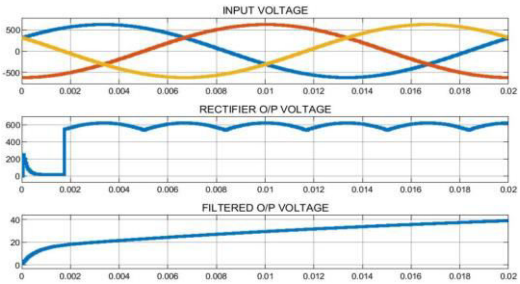


Figure 8: Simulink model input voltage and rectified output voltages

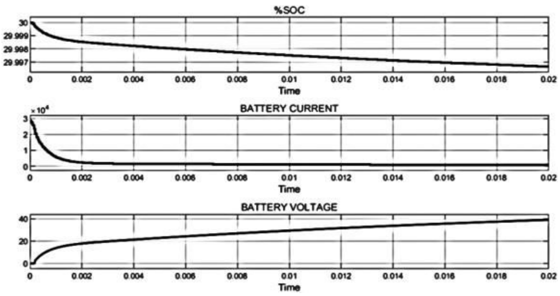


Figure 9: Simulink results for SCR based full-bridge controlled rectifier

B. Twelve-Pulse Diode Bridge Rectifier Followed by Full-Bridge DC–DC Converter (Topology-II)

The Simulink model for this topology is depicted in Figure 10. To achieve closed-loop operation, a Proportional-Integral-Derivative (Proportional-Integral-Derivative) control system is integrated into the simulation. This configuration maintains a battery charging voltage of 56 V, with the current loop ensuring a maximum charging current of 80 A. The system dynamically adjusts the duty cycle of two insulated-gate bipolar transistors (IGBTs) based on the battery's charging requirements. When the battery voltage is below 56 V, the system allows a maximum charging current of 80 A. As the battery voltage approaches 56 V, the charging current gradually tapers off by reducing the duty cycle, ensuring smooth and safe transition to the constant voltage phase. Figure 11 ilustrate the Simulink model H-bridge pulse controlling model. Figure 12 illustrates the pulse generation mechanism, where a pulse generator provides signals to the switches. This pulse-driven approach ensures synchronized operation of the thyristors and switches, contributing to efficient performance. The high switching frequency of the full-bridge DC–DC converter reduces current ripple to less than 0.5%, resulting in smoother operation and better charging performance. The inclusion of the twelve-pulse diode bridge rectifier minimizes input current harmonics, improving power quality and reducing strain on the power grid. This topology requires a high-frequency transformer and high-frequency diodes for proper operation, which increases complexity and cost. Additionally, the system incorporates two transformers, further contributing to the overall expense of the design. Figure 13 showcases the Simulink results for this topology, demonstrating its performance and highlighting its effectiveness in maintaining stable charging conditions. Despite its higher cost, this design is particularly suitable for applications demanding high efficiency, low harmonic distortion, and precise control.

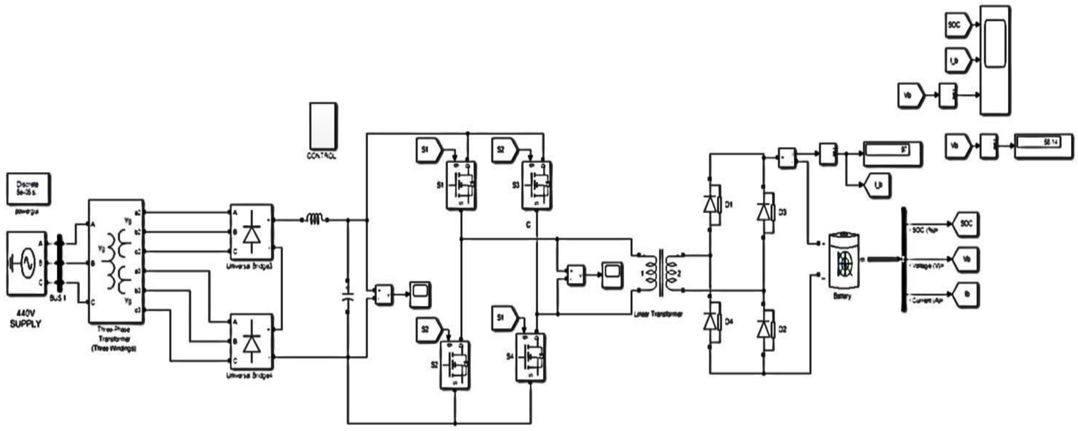


Figure 10: Simulink model for twelve pulse diode bridge rectifier followed by a full-bridge DC-DC converter

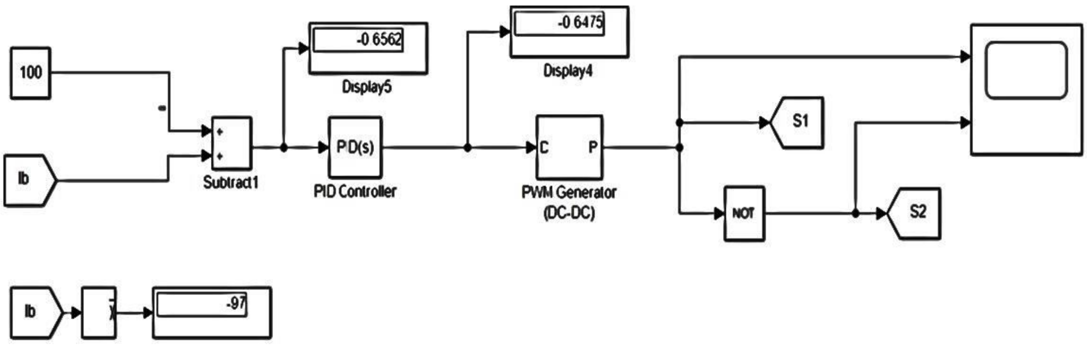
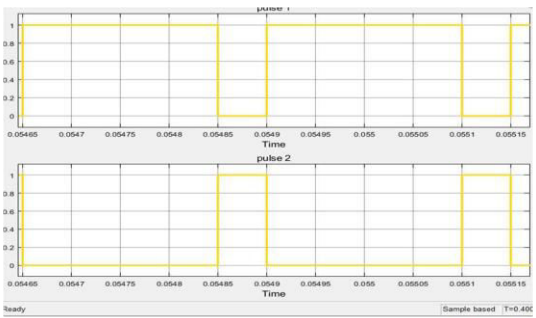


Figure 11: Simulink model H-bridge pulse controlling model



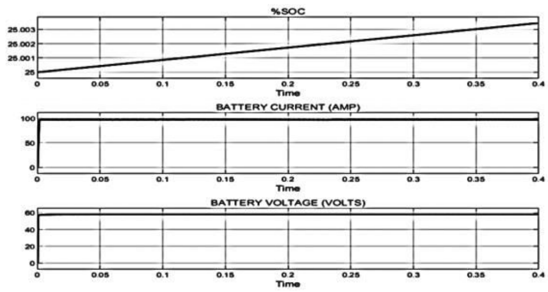


Figure 12. Pulse generator is used to have thyristor 4 pulses

Figure13: Simulink results for twelve pulse diode bridge rectifiers followed by the full-bridge DC-DC converter

C. Six-Pulse Thyristor Bridge Rectifier Followed by Full-Bridge DC–DC Converter (Topology-III)

In this power configuration, the rectification stage uses a six-pulse Silicon Controlled Rectifier (silicon-controlled rectifier)-based controlled rectifier instead of the uncontrolled diode bridge rectifier employed in earlier topologies. The DC-to-DC full-bridge converter stage, however, remains the same as in the preceding design. One key advantage of this topology is its flexibility in adjusting the DC output voltage to match the battery's requirements by varying the firing angle of the Silicon Controlled Rectifier. Unlike the fixed DC voltage in the previous topology, this two-way control capability provides greater adaptability for charging batteries with different voltage specifications. Despite its improved control, this topology has certain drawbacks. The use of the Silicon Controlled Rectifier bridge increases input current harmonics and reduces the input power factor compared to the twelve-pulse diode bridge rectifier in Topology-II. Figure 14 illustrates the Simulink model for this topology. The Proportional-Integral-Derivative control model, as described in Figure 11, can also be utilized in this design with the same parameters and settings to maintain stable operation and adhere to the desired constant current (Constant Current) and constant voltage (Constant Voltage) charging profiles. In this design, the six-pulse thyristor bridge is employed at the primary stage to regulate the DC link voltage effectively. However, the use of the Silicon Controlled Rectifier bridge inherently lowers the input power factor, which is a trade-off for the added control over the output voltage. The generated corresponding input voltages and rectified output are shown in Figure 15. The Simulink results for this topology, shown in Figure 16, display the battery parameters over time, highlighting the system's performance. This topology is well-suited for applications requiring adjustable voltage output, but its lower power factor and higher harmonic content may necessitate additional power quality measures in grid-connected scenarios.

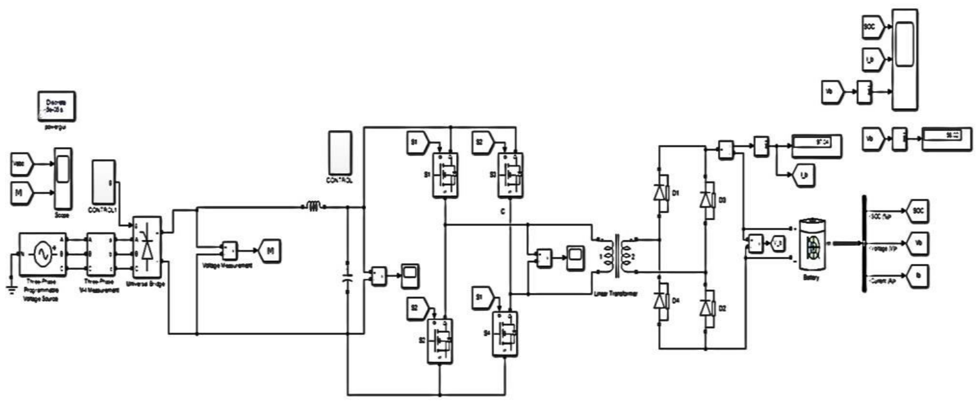


Figure. 14: Simulink model for six pulse thyristor bridge rectifiers followed by a full-bridge DC-DC converter

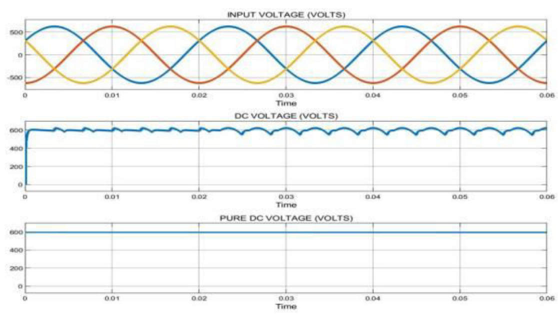


Figure 15. Simulink model input voltage and Rectified voltages

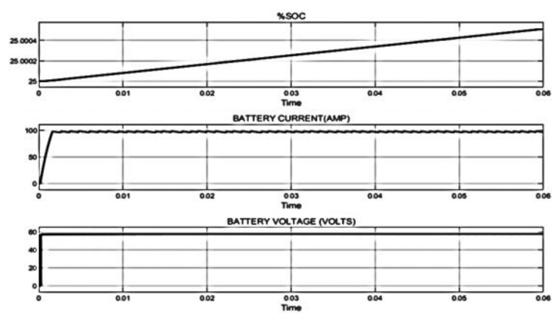


Figure 16. Simulink results for six pulse thyristor bridge rectifiers followed by a full-bridge DC-DC converter

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D. Twelve-Pulse Diode Bridge Rectifier Followed by Midpoint Clamped Three-Level Buck Converter (Topology-IV)

This power topology incorporates a twelve-pulse diode bridge rectifier to generate a rectified DC voltage. The subsequent stage consists of a midpoint clamped three-level buck converter. This converter design uses two capacitors to halve the voltage stress on each power switch, enhancing the system's reliability and efficiency. The three-level buck converter operates in three distinct modes: Both switches ON., Only one switch ON. Both switches OFF. These operating modes have been explained in prior sections. A dual Proportional-Integral-Derivative loop control mechanism is implemented in the simulation, as shown in Figure 17. The outer Proportional-Integral-Derivative loop regulates the battery charging voltage to 57.6 V, while the inner current loop maintains a maximum charging current of 100 A. The duty cycle of the two insulated-gate bipolar transistors (IGBTs) is adjusted based on the battery's voltage and current requirements. When the battery voltage is below 57.6 V, the system permits a maximum charging current of 100 A for rapid charging. Once the battery voltage reaches 57.6 V, the current gradually tapers off as the duty cycle decreases, ensuring a smooth transition to the constant voltage phase

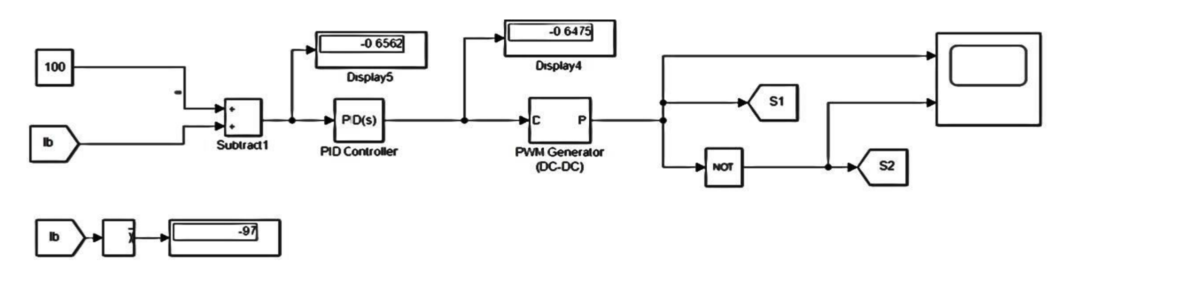

Figure. 17: Simulink model H-bridge pulse controlling model

Figure 18 presents the Simulink model for this topology. The inclusion of the twelve-pulse diode bridge rectifier ensures a high input power factor, improving overall system efficiency. Additionally, the midpoint clamped three-level buck converter reduces both current and voltage stress by half, as each power switch is exposed to only half the total voltage. This reduction in stress contributes to a more economical and durable design.

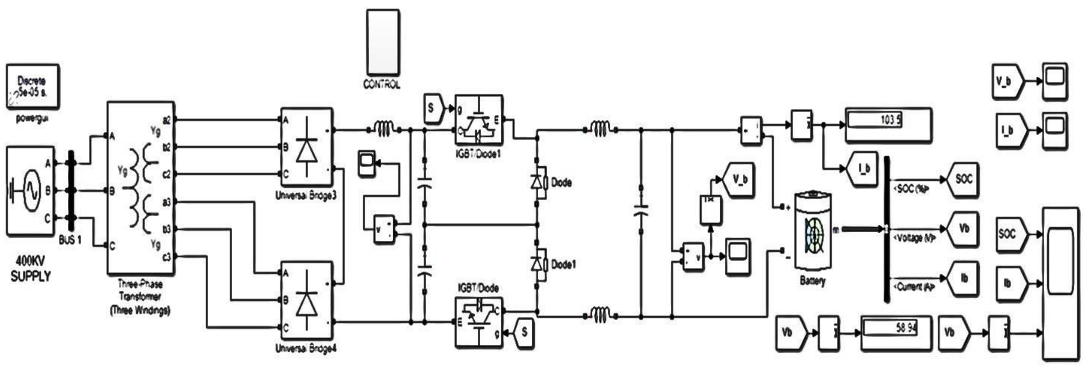

Figure. 18: Simulink model for twelve pulse diode bridge rectifier

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Figure 19 illustrates the input line and phase voltage as well as the input current in the Simulink model. The system demonstrates superior power quality due to the high input power factor and reduced harmonic distortion. The Simulink results for this topology, including battery parameters over time, are shown in Figure 20. These results validate the effectiveness of the design, showcasing its ability to deliver efficient charging while minimizing voltage stress on components, making it a robust and cost-effective solution for high-performance applications.

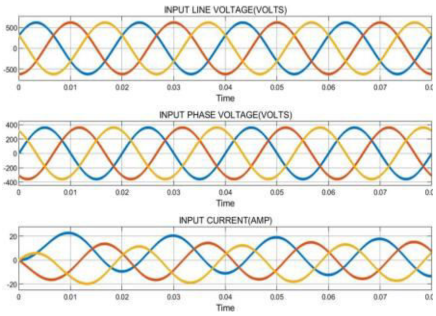

Figure 19: Simulink model input line and phase voltage and input current

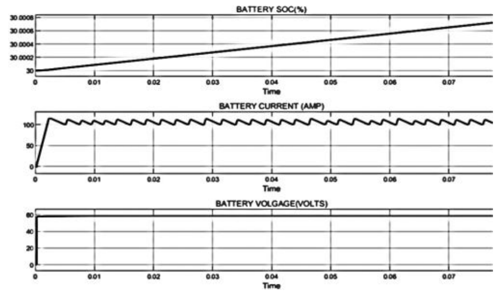

Figure. 20.: Simulink results for twelve pulse diode bridge rectifier

4. Conclusion

In this paper, four distinct charging topologies have been analyzed and compared based on their MATLAB simulations. Topology-I, featuring an Silicon Controlled Rectifier-based full-bridge controlled rectifier, is the simplest to implement and offers robust operation. However, it suffers from higher battery current ripple and a low power factor. In Topology-II, the twelve-pulse diode bridge rectifier is followed by a full-bridge DC-DC converter, providing better control and a higher power factor. However, this topology comes at a higher cost due to the need for high-power components such as high-frequency transformers and diodes. Topology-III replaces the twelve-pulse diode bridge with a six-pulse Silicon Controlled Rectifier bridge, maintaining the full-bridge DC-DC converter. This design retains the same cost implications as Topology-II but suffers from a lower input power factor. After comparing all the topologies, it is evident that Topology-IV, which integrates the twelve-pulse diode bridge rectifier with a midpoint clamped three-level buck converter, is the most suitable for electric vehicle (Electric Vehicle) charging applications. This topology offers significant advantages, including reduced voltage and current stress, lower thermal stress, decreased system complexity, and, most importantly, enhanced control over battery parameters, making it an ideal choice for efficient and reliable Electric Vehicle charging solutions.

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