**FMDB** *Transactions on Sustainable Energy Sequence*

# Hybrid On-Board Battery Energy Storage System with a Soft-Switching Full-Bridge Converter for Electric Vehicle Charging Applications

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**Abstract:** The Soft-Switching Full-Bridge (SSFB) converter and Half-Bridge (HB) LLC resonant converter in this research constitute a hybrid DC-DC converter for on-board chargers. The hybrid architecture aims to achieve high conversion efficiency, low switching losses, voltage management, and reliable operation under various charging conditions. The secondary-side switch and diode limit circulating current and allow full soft switching of the SSFB converter's primary-side switches. The proposed design reduces circulating current and switching losses, improving efficiency and power management in high-frequency electric-vehicle charging converters. Closed-loop secondary-side switch duty cycle control modulates converter output voltage. This study explores a phase-shift-modulated, high-frequency full-bridge resonant DC-DC converter with efficient power transfer and accurate output-voltage regulation. Proportional-integral-derivative (PID) and sliding-mode closed-loop control are examined. Performance is compared using overshoot, rise time, settling time, and steady-state error. Sliding-mode controllers are more resistant to parameter changes, load disturbances, and nonlinear operating conditions than PID controllers. The small-signal model evaluates the converter's dynamic characteristics and supports closed-loop controller design. The mathematical model shows how to adjust converter variables and controller settings for rapid, reliable operation. MATLAB/Simulink simulations test the topology and control methods under varying input voltage, load, and operating conditions. Experimental results confirm the simulations and demonstrate the design's feasibility. The hybrid converter's dynamic response, output-voltage regulation, switching losses, and steady operation make it better suited for high-frequency on-board electric-vehicle charging systems.

**Keywords:** Half-Bridge (HB); Sliding-Mode Control; PID Controllers; Soft Switching; Output-Voltage Regulation; Resonant Converter; Closed-Loop Control; High Conversion Efficiency.

**Received on:** 08/10/2024, **Revised on:** 17/12/2024, **Accepted on:** 22/02/2025, **Published on:** 05/10/2026

**Journal Homepage:** https://www.fmdbpub.com/user/journals/details/FTSES

**DOI:** https://doi.org/10.69888/FTSES.2026.000794

**Cite as:** S. Nekrasov, H. Kardoush, S. Masri, S. Manivannan, G. A. A. Alrefai, and L. Chun-Kit, "Hybrid On-Board Battery Energy Storage System with a Soft-Switching Full-Bridge Converter for Electric Vehicle Charging Applications," *FMDB Transactions on Sustainable Energy Sequence*, vol. 4, no. 2, pp. 68–83, 2026.

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## 1. Introduction

This paper proposes a hybrid DC–DC converter for on-board charger applications [10]. The hybrid DC–DC converter comprises a Soft-Switching Full-Bridge (SSFB) converter and a Half-Bridge (HB) LLC resonant converter. The proposed hybrid topology aims at high efficiency, low switching losses, high power density, and better voltage regulation for modern electric-vehicle charging systems. An extra switch and diode on the SSFB converter's secondary side eliminate circulating current and enable full soft-switching of the primary-side switches [11]. The proposed converter reduces circulating current, lowering unnecessary conduction losses and improving overall power-conversion efficiency. Additionally, the output voltage is regulated by varying the secondary-side switch duty cycle. This method effectively regulates the output voltage under variations in input voltage and load conditions. The converter is especially suitable for high-frequency operation because soft-switching reduces switching stress and electromagnetic interference, allowing higher switching frequencies [12]. To have a constant output voltage under different operating conditions, a suitable closed-loop control strategy is required. Thus, phase-shift modulation is considered to control the high-frequency full-bridge resonant DC–DC converter. This paper studies closed-loop control of the phase-shift-modulated high-frequency full-bridge resonant DC-DC converter using Proportional-Integral-Derivative (PID) and sliding-mode control techniques. The dynamic responses of the two techniques are compared in terms of overshoot, rise time, settling time and steady-state error [13]. The PID controller is a relatively simple, practical control structure for controlling the output voltage. The sliding-mode controller has better robustness to parameter variations and disturbances.

To simplify controller design and evaluate the system's dynamic characteristics, researchers extract a small-signal model of the converter. MATLAB/Simulink simulations and experimental results validate the converter's performance and feasibility under various input-voltage, load and switching conditions. The results show the effectiveness of the proposed topology and control methods for high-performance battery-charging applications. As more renewable energy sources are integrated and electric transportation develops rapidly, efficient power conversion technologies are becoming increasingly important [15]. Conventional electrical distribution systems face rising power demand and limited supply capacity and reach in densely populated urban areas. Efficient power-electronic converters with lower losses and better controllability can address these challenges. In particular, resonant DC-DC converters have attracted considerable attention for their soft-switching capability, high efficiency, high-frequency operation, and reduced electromagnetic interference [16]. The LLC resonant converter is a widely studied topology for applications such as battery chargers, renewable-energy systems, data centers, and electric vehicles. The authors propose an LLC resonant DC–DC converter for low-voltage distribution systems [1]. The LLC converter offers good switching characteristics and can operate with soft switching across a wide operating range. Soft switching greatly reduces switching losses compared with conventional hard-switched converters. As switching frequency increases, semiconductor switching losses worsen, so zero-voltage switching (ZVS) or zero-current switching (ZCS) is required for high efficiency. The LLC resonant converter addresses this problem by using a resonant inductor, resonant capacitor and transformer magnetizing inductance to shape the current and voltage waveforms during switching transitions.

Uses a full-bridge LLC resonant converter to transfer energy from the primary side to the secondary side [2]. The full-bridge topology is especially beneficial in high-power applications because it uses the available input voltage more effectively and shares the power across multiple semiconductor devices. The LLC converter also provides soft-switching on the primary-side switches when the switching frequency is properly set. ZVS greatly reduces turn-on losses and voltage stress on the switching devices. This feature makes the full-bridge LLC converter attractive for high-power electric vehicle chargers and other high-voltage DC-DC conversion applications. The resonant and switching frequency should be properly selected to operate the converter in the desired soft-switching region. Zhang et al. [3] present and analyse the operating modes of a full-bridge LLC resonant converter. The paper investigates the converter's voltage-gain characteristics and impedance behavior in detail and selects circuit parameters according to the desired operating conditions. The gain characteristics are particularly important because the LLC converter controls the output voltage by changing the switching frequency rather than the duty ratio directly. Impedance characteristics affect current distribution in the resonant components and semiconductor devices and, consequently, influence converter efficiency and switching performance [18]. The study provides useful information for selecting the resonant inductance, resonant capacitance, magnetizing inductance and transformer parameters to achieve the desired voltage gain and soft-switching range. The study also examines a soft-switching full-bridge DC-DC converter for electric vehicle applications. Electric cars need high-voltage, high-power charging systems that can deliver a large amount of energy in a relatively short charging time [17].

High-voltage and high-power electric vehicle charging systems can be designed using a voltage-doubler rectifier. By combining a battery system, a soft-switching DC-DC converter, and an ultracapacitor bank, this approach addresses low specific power, high voltage spikes across the rectifier diode, and performance during both acceleration and regenerative braking [4]. Coupling

an ultracapacitor with a battery may improve the energy-storage system's ability to respond to rapid increases in power demand. The battery can provide relatively sustained energy, while the ultracapacitor can supply or absorb high transient power during acceleration and regenerative braking. Efficient bi-directional or controlled DC-DC conversion stages are needed for proper energy management in such hybrid energy-storage systems. Control techniques are critical to the dynamic and steady-state behavior of LLC resonant converters. The authors propose a sliding-mode plus proportional-integral control scheme with self-sustained phase-shift modulation for LLC resonant converters [5]. The proposed control schemes improve the transient response while maintaining satisfactory steady-state performance. For the sliding-mode controller design, researchers develop an averaged large-signal model of the LLC converter with ZVS modulation. The large-signal model allows the controller to account for nonlinear behavior and large variations in operating conditions. Sliding-mode control is particularly attractive for power converters because it is robust to parameter uncertainties, input voltage variations and load disturbances [19]. However, the controller must be designed to minimize undesirable effects such as chattering and excessive switching activity. A full-bridge LLC resonant converter with two operating modes, full-bridge and frequency-doubler, is proposed for applications requiring a wide voltage-gain range [6].

## 2. Review of Literature

The demand for high-efficiency, compact, and dynamically stable DC–DC converters has grown dramatically with the advent of electric-vehicle (EV) charging systems and other high-power energy conversion applications. In battery charging systems, the battery voltage fluctuates significantly between a low state of charge and a fully charged state. Thus, the DC-DC converter must provide a sufficiently wide voltage-gain range while maintaining good voltage control, high efficiency and low semiconductor stress. LLC resonant converters have attracted much interest because of their soft-switching operation, high-frequency operation, reduced switching losses, and high-power density. Lei et al. [1] studied the design of a full-bridge LLC resonant DC–DC converter and examined its energy transfer and mathematical features in different operating modes. Their study also covers resonant-parameter design and verifies the proposed converter through simulation and experimental results, highlighting the importance of selecting resonant components to meet required converter performance. The full-bridge LLC converters have also been studied for applications demanding variable power transmission and high efficiency. Wu and Han [2] proposed a full-bridge LLC converter with wireless power transmission and dual-mode output. The proposed system used the wireless power-transfer structure's leakage inductance as part of the resonant network and demonstrated soft-switching behaviour of the primary switches. Experimental results show that the converter can deliver DC and AC outputs, demonstrating the versatility of LLC-based topologies for various energy-conversion applications [14]. Similarly, Zhang et al. [3] designed a digitally controlled full-bridge LLC resonant converter employing a digital signal processor.

Their work used frequency-control techniques to regulate output voltage and maintain soft switching. A prototype with a 400-V input and 48-V/600-W was built, and the experimental findings verified the suggested concept [20]. The study shows that digital control can provide accurate voltage regulation while retaining the soft-switching advantages of LLC architecture. Soft-switching is crucial for EV applications because switching losses increase at high frequencies. Jelaja and Rajaram [4] studied a soft-switching full-bridge DC–DC converter for electric-vehicle applications. They combined a soft-switching converter and a voltage-doubler rectifier with energy-storage features to meet the high-voltage and high-power needs of EV systems. The results showed that soft-switching approaches can reduce switching stress and improve converter performance, making them suitable for high-power EV charging and regenerative-braking applications. Another major issue in LLC converter design is control. Zheng et al. [5] proposed a combined sliding-mode and proportional-integral control technique for a full-bridge LLC resonant converter. Their approach included self-sustained phase-shift modulation and an averaged large-signal model for controller design. The proposed control scheme improved transient performance while preserving good steady-state behavior. Combining sliding-mode control with PI control also improved resilience and fast response to load changes while maintaining zero-voltage-switching operation. One of the main difficulties in practical battery-charging applications is the need for a large voltage-gain range. Conventional LLC converters are commonly controlled by varying the switching frequency for voltage regulation. When the output or input voltage varies greatly, this strategy can require a very wide switching-frequency range, complicating magnetic-component design, increasing control complexity, and potentially increasing circulating current and conduction losses.

To overcome this constraint, Wei et al. [6] proposed a full-bridge LLC converter with two operating modes: full-bridge mode and frequency-doubler mode. The proposed method extends the voltage-gain range while minimizing the needed switching-frequency range. The authors also used switching-frequency feedforward control to enable smooth transitions between operating modes. The authors experimentally validated the proposed technique's efficiency on a 150 W prototype. They also studied LLC converters for railway and other high-power applications, focusing on resonant-tank design and operation. Han et al. [7] examined design and simulation verification of a full-bridge LLC resonant converter. The study investigated the resonance parameters and operating conditions needed to achieve gentle switching across a wide range of loads. The paper emphasizes the need to select resonant parameters properly for stable, effective operation [21]. In battery charging applications, closed-loop voltage management is necessary because battery voltage and load conditions change constantly during charging.

Shahzad et al. [8] proposed an LLC series-resonant converter with a PID controller for battery charging. A PID controller controls the switching frequency generated by a voltage-controlled oscillator to regulate the converter output voltage. They simulated an input range of about 380-420 V and an output range of 28-72 V. This shows that PID control can respond to line voltage, load and reference voltage variations. Joseph et al. [9] presented closed-loop control of a full-bridge LLC resonant converter in another battery charging investigation.

The authors noted that soft-switching methods can reduce switching losses and improve the reliability of high-frequency battery chargers [22]. They presented an LLC converter with closed-loop control for output regulation, reducing low- and high-frequency battery current ripple and improving battery operating conditions and longevity. The literature shows that LLC resonant converters offer advantages such as gentle switching, high efficiency, high power density and low switching stress. However, traditional LLC converters may struggle under wide variations in input voltage, output voltage and load. In particular, large switching-frequency variation can make magnetic-component design and control-circuit design difficult. Circulating current can increase conduction losses [23].

The literature has addressed these difficulties through digital control, PID control, sliding-mode control, phase-shift modulation, multiple operating modes, and topology adjustments. However, a converter that provides gentle switching, low circulating current, high voltage gain, small switching-frequency changes, and strong closed-loop control is still required. Thus, the proposed hybrid converter combines a soft-switching full-bridge converter with a half-bridge LLC resonant converter. The added secondary-side switching mechanism provides an additional degree of freedom for voltage regulation, and phase-shift modulation and closed-loop control can increase transient performance [24]. Further comparative evaluation of PID and sliding-mode controllers in terms of rise time, overshoot, settling time, and steady-state error can demonstrate the system's effectiveness. The converter can be initially evaluated through MATLAB/Simulink simulations and then validated experimentally under different input-voltage and load conditions.

## 3. Methodology

This work uses the proposed design, modeling, simulation, and performance evaluation of the hybrid DC-DC converter for on-board charger applications. This hybrid topology combines the SSFB converter and the HB LLC resonant converter. On the SSFB converter's secondary side, an additional switch and diode reduce circulating current and enable soft switching of the primary-side switches. The switching parameters and resonant elements are selected according to the required input and output voltage specifications. To investigate the converter's performance under steady-state and dynamic conditions, we develop a mathematical and small-signal model. Using MATLAB/Simulink, the converter is built for both open-loop and closed-loop analysis. Phase-shift modulation controls the high-frequency full-bridge resonant stage, and the secondary-side switch duty cycle is adjusted to regulate the output frequency. The converter control system implements PID and SMC as two closed-loop control approaches. Performance is evaluated under various source and load disturbances, as well as various input-voltage and load conditions. The metrics used to analyze the acquired responses are overshoot, rise time, peak time, settling time, and steady-state error. Finally, the simulation results are compared to determine which control technique achieves rapid, stable, and accurate voltage regulation of the hybrid converter more efficiently.

### 3.1. System Description

The proposed block diagram of the resonant DC-DC converter with a Π-filter for the open-loop system is shown in Figure 1. Figure 2 shows the closed-loop simulation block diagram of the onboard charging DC-DC converter with a PID/SM-controlled system.

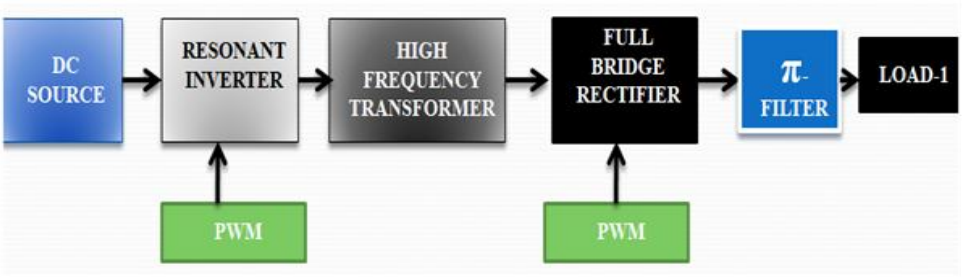



**Figure 1:** Proposed block diagram of resonant DC-DC converter with π-filter

Industrial control systems and other applications that require continuous modulation often use feedback control loops known as proportional-integral-derivative (PID) controllers, or three-term controllers.

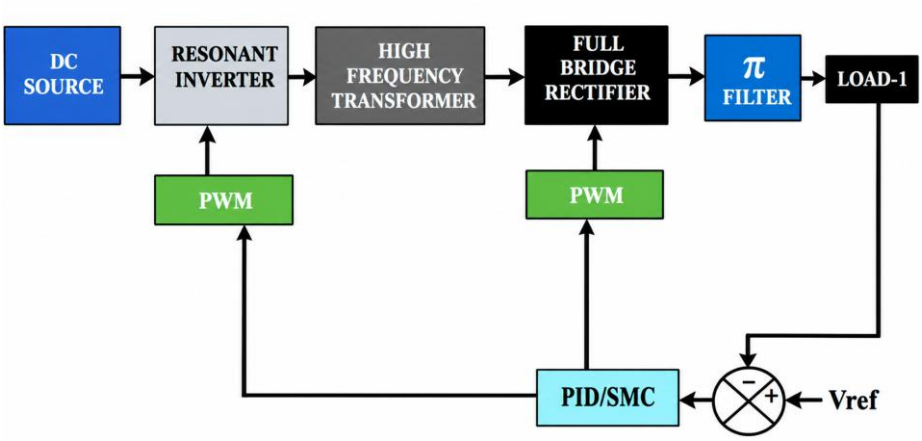



**Figure 2:** Closed-loop simulation block diagram of onboard charging DC-DC converter with PID/SM controlled system

A PID controller continuously calculates an error. The fundamental idea is to read a sensor, calculate the required actuator output using proportional, integral, and derivative responses, and sum them (Figure 3).

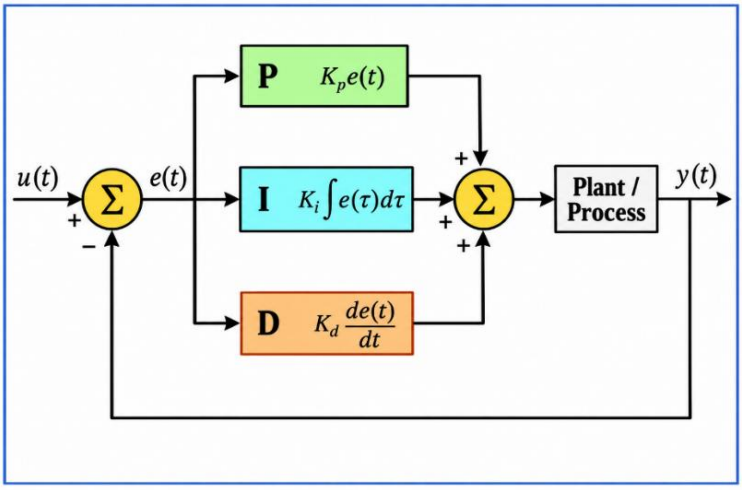



**Figure 3:** Block diagram of PID controller

### 3.2. Sliding Mode Controller

Figure 4 shows the 'SMC' block diagram. One or more system states in the sliding surface form the core of the SMC controller. To stabilize the system, some controllers also include inaccuracies in the sliding surface and its time derivatives.

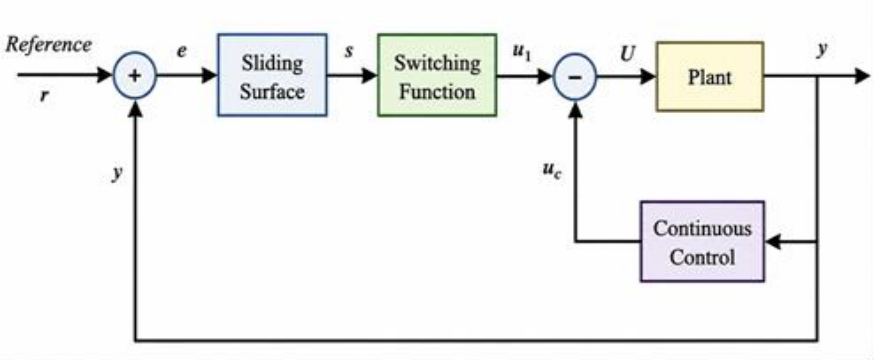



**Figure 4:** Block diagram of sliding mode controller

In this scenario, the sliding surface can be represented as a second-order differential equation, which requires extensive numerical analysis to ensure system stability. To improve steady-state error and settling time, researchers define another surface that includes voltage error and the square of the capacitor current.

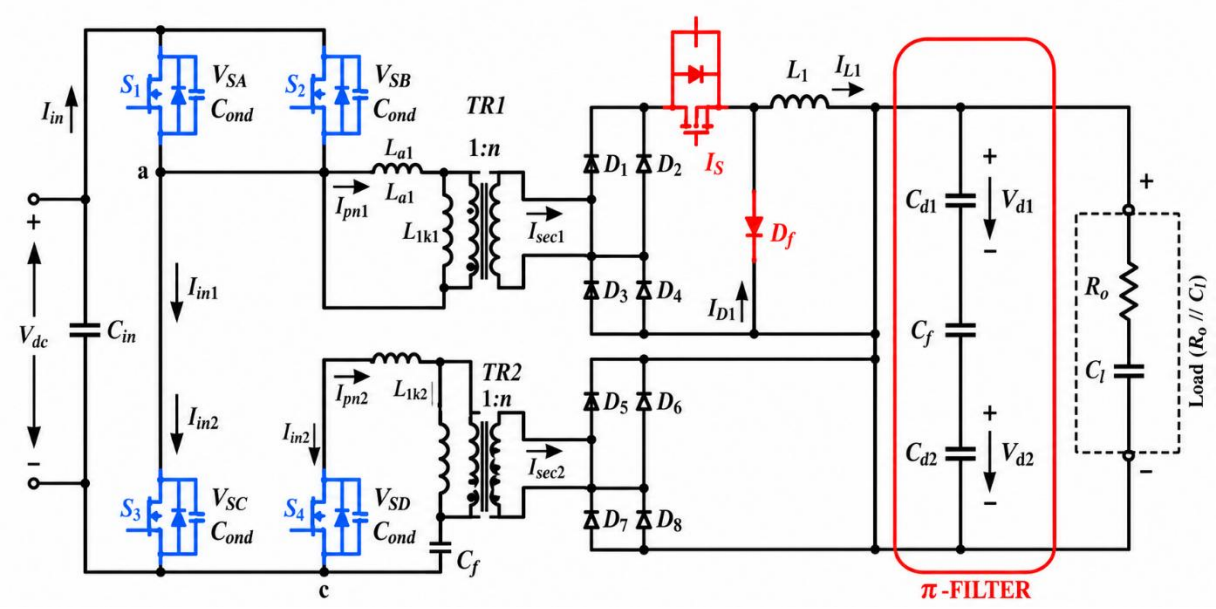



**Figure 5:** Proposed open-loop circuit diagram of resonant DC-DC converter with π-filter system

The proposed open-loop circuit diagram of the resonant DC-DC converter with a π-filter system is shown in Figure 5. The proposed closed-loop circuit diagram of the resonant DC-DC converter with a π-filter system with PID and SMC systems is shown in Figure 6.

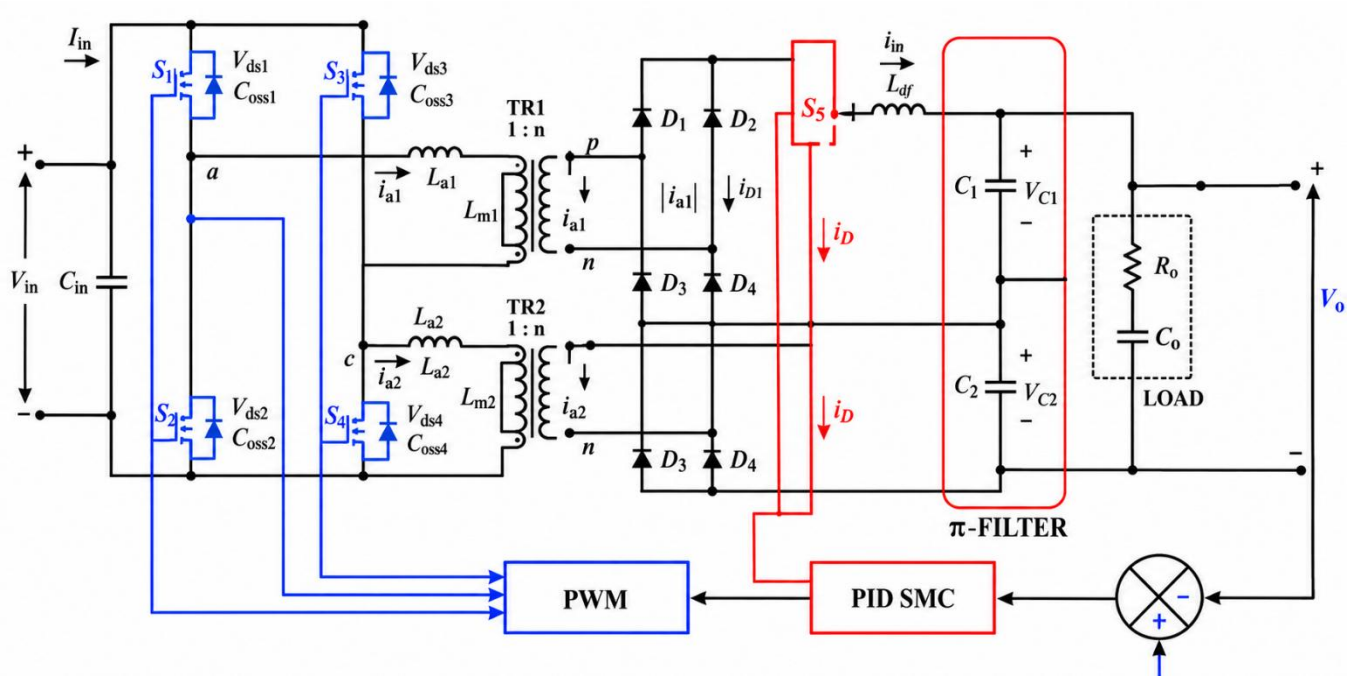



**Figure 6:** Proposed closed-loop circuit diagram of resonant DC-DC converter with PID/SMC system

## 4. Results and Discussions

### 4.1. Open-Loop Proposed Resonant DC-DC Converter with Π-Filter for Source Disturbance System

Figure 7 shows the circuit diagram of the proposed resonant DC-DC converter with a π-filter for the source-disturbance system.

**Table 1:** Simulation parameters of modified LLC resonant converter

| **Vin** | **20V** |
|---|---|
| $L_2$, $L_6$ | 0.5µH |
| $L_4$, $L_5$ | 30 µH |
| $L_1$, $L_3$ | 1µH |
| $C_4$ | 100µF |
| $C_1$, $C_3$, $C_5$ | 2200 µF |
| $C_2$ | 0.05 µF |
| R | 0.001 Ω |
| MOSFET | IRF840 |
| Diode | IN4007 |
| Vo | 49V |

Figure 8 shows the input voltage, which is 20V. Table 1 presents the simulation parameters.

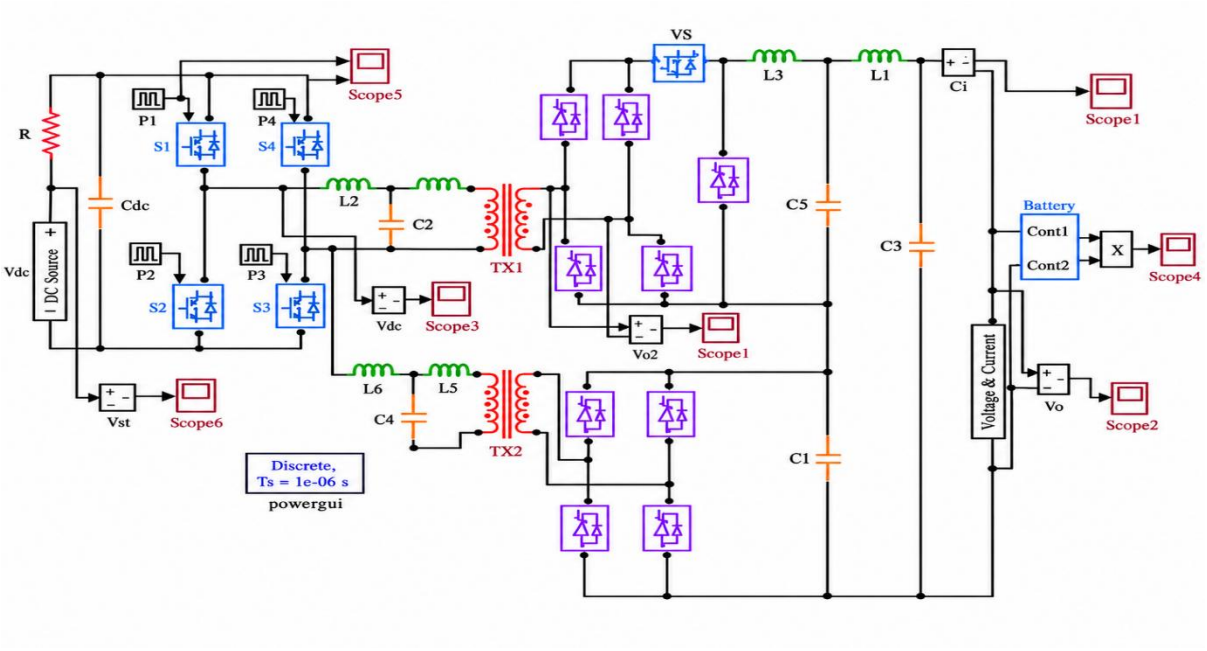



**Figure 7:** Circuit diagram of proposed resonant DC-DC converter with π-filter for source disturbance system

Figure 8 shows that the input voltage Vin increases from 15 V to 20 V at around 0.6 sec and then remains constant.

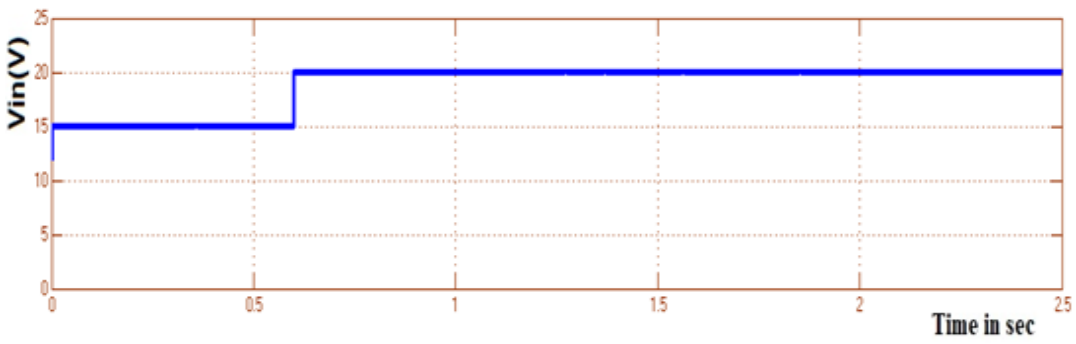



**Figure 8:** Input voltage

Figure 9 shows the output voltage across the motor load. The value is 66V.

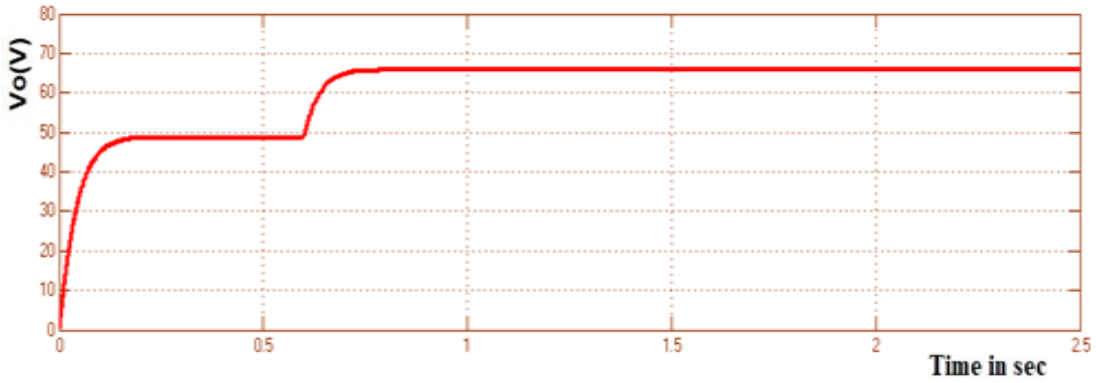



**Figure 9:** Output voltage across motor load

Figure 10 shows the output current through the motor load. The value is 1.4A.

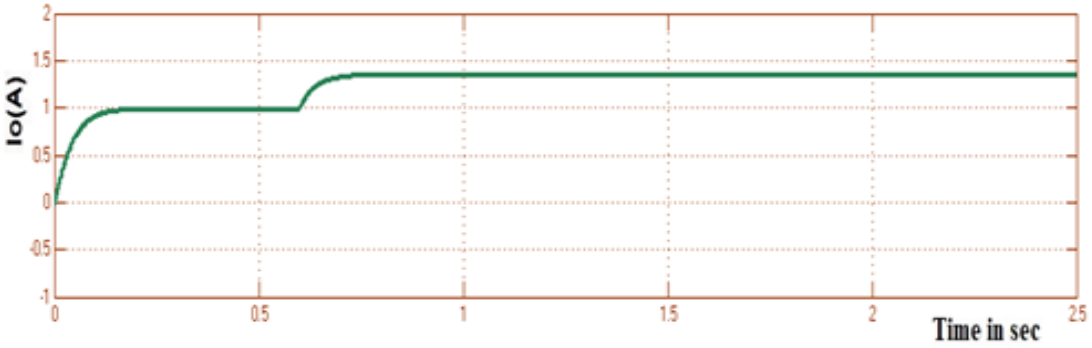



**Figure 10:** Output current through motor load

Figure 11 shows the output power, which is 92W.

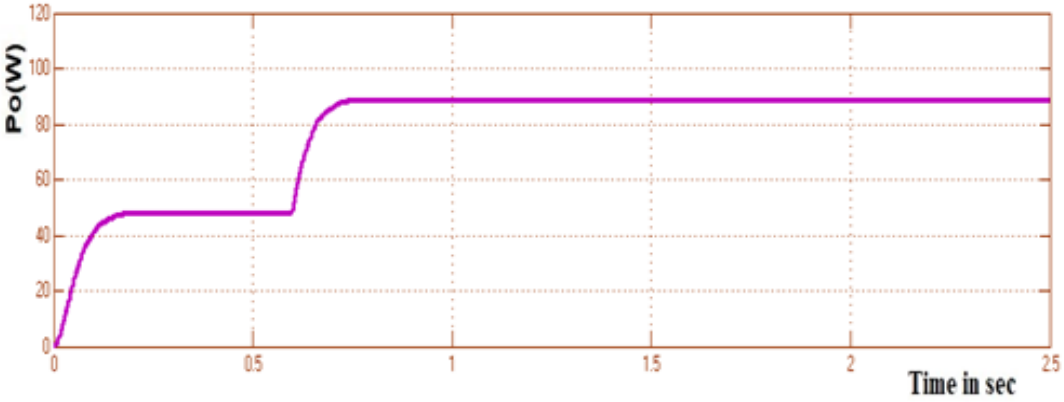



**Figure 11:** Output power

### 4.2. Closed-Loop Proposed Resonant DC-DC Converter with Π-Filter for PID Controller System

Figure 12 shows the circuit diagram of the closed-loop proposed resonant DC-DC converter with a π-filter for the PID controller system. Figure 12 shows the input voltage, which is 20V.

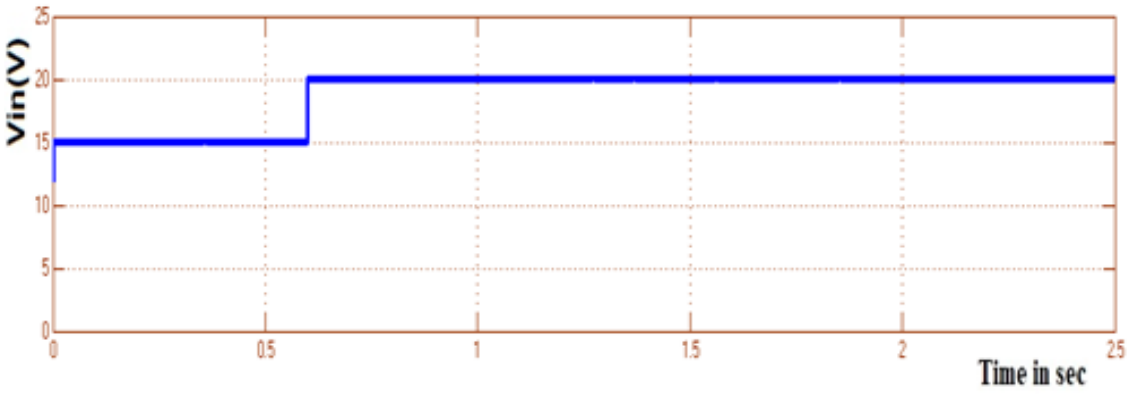



**Figure 12:** Input voltage

Figure 13 shows the output voltage across the motor load of the resonant DC-DC converter with a π-filter for the closed-loop PID controller system; its value is 49V.

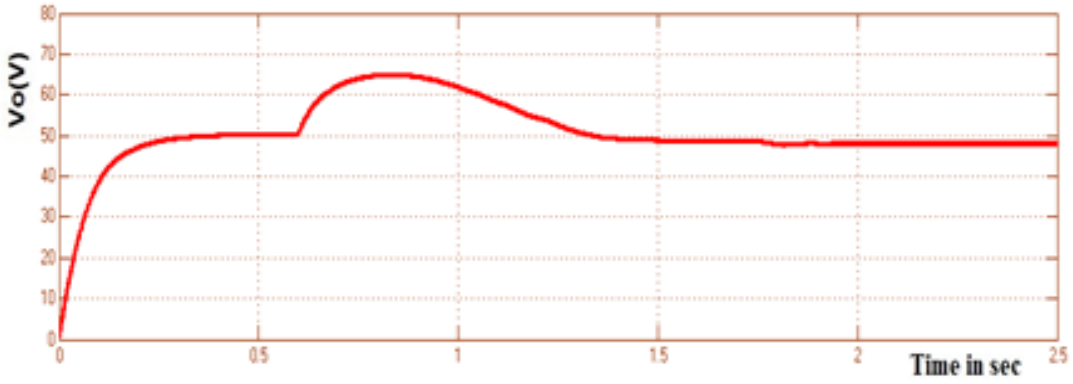



**Figure 13:** Output voltage across motor load

Figure 14 shows the output current through the motor load of the resonant DC-DC converter with a π-filter for the closed-loop PID controller system; its value is 1A.

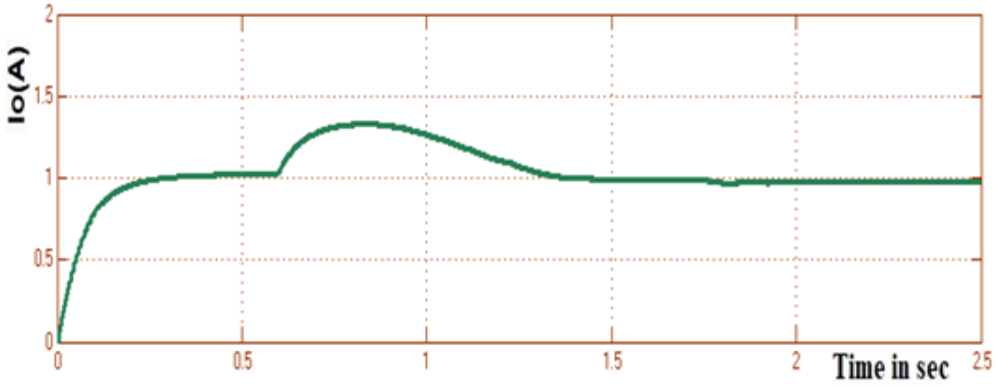



**Figure 14:** Output current through motor load

Figure 15 shows the output power across the motor load of the resonant DC-DC converter with a π-filter for the closed-loop PID controller system; its value is 48W.

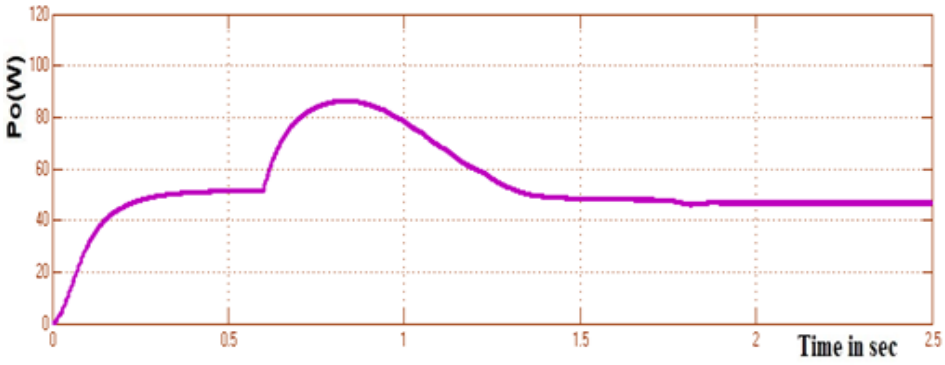



**Figure 15:** Output power across motor load

### 4.3. Closed-Loop Proposed LLC Resonant Converter with SM Controller System

Figure 17 shows the circuit diagram of the proposed closed-loop resonant DC-DC converter with a π-filter for the sliding mode controller system 17. Figure 16 shows the input voltage18, which is 20V. Figures 16 and 17 show the input and output voltage responses of the proposed system over 0 to 2.5 seconds. Figure 16 is the voltage (Vin) over time.

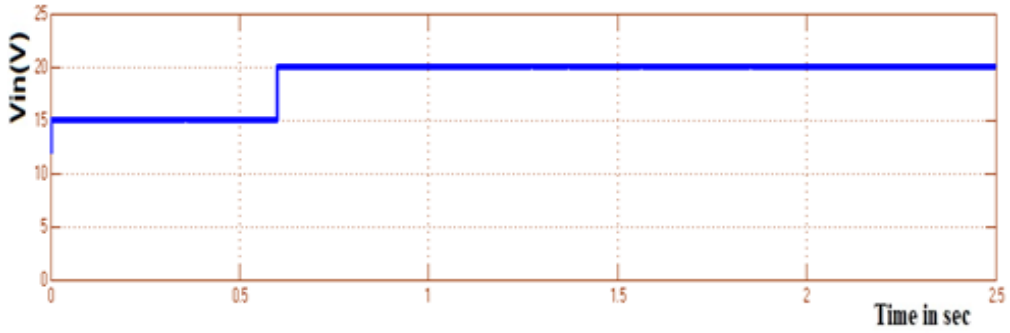



**Figure 16:** Input voltage

The input voltage is roughly steady from 0 to around 0.6 s at about 15 V. At around 0.6 seconds, the input voltage suddenly steps from 15 V to 20 V. After this transition, the voltage remains steady around $\sim$20 V for the duration of the simulation time. This steep change shows that the system responds quickly to changes in the applied input voltage.

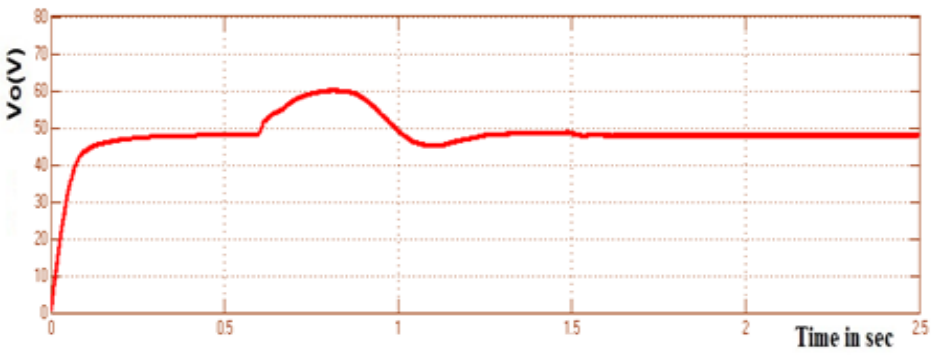



**Figure 17:** Output voltage across motor load

Figure 17 shows the system's response in terms of output voltage (Vo). At the start of the simulation, the output voltage rises quickly from almost zero to about 45–48 V and then stays nearly constant until the input-voltage step at roughly 0.6 seconds. After the input-voltage step, the output voltage rises steadily. It reaches a maximum of about 60 V.

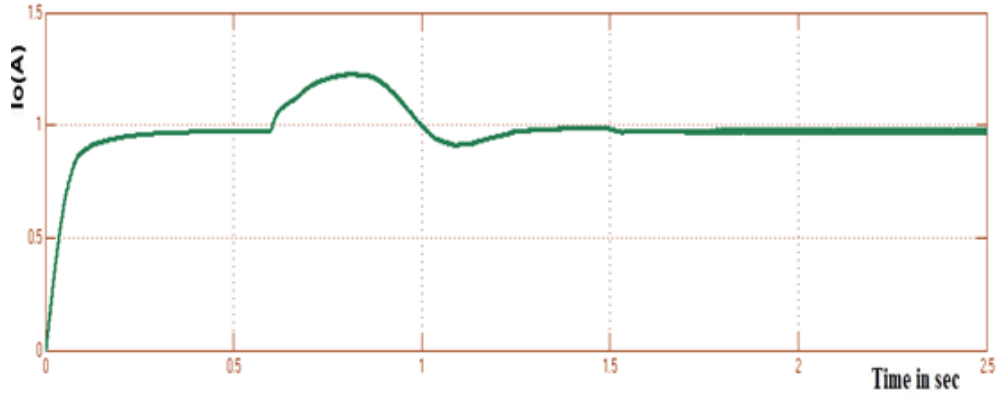



**Figure 18:** Output current through motor load

After this peak, the output voltage drops, with a small transient oscillation before returning to steady state. At around 1.1 s, the output voltage returns to approximately 47-48 V and stays nearly stable until the end of the simulation. It generally shows the system's dynamic and steady-state characteristics for a step change in input voltage.

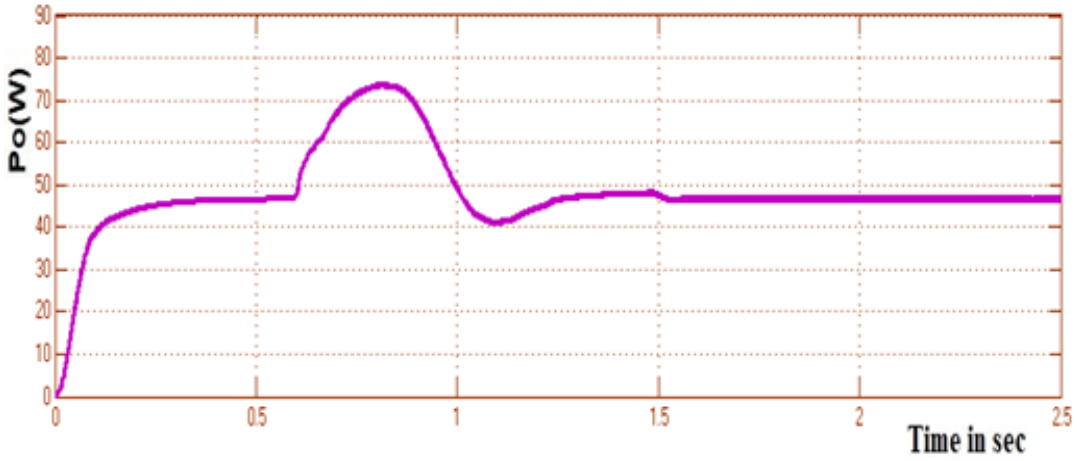



**Figure 19:** Output power across motor load

The output response shows a transient disturbance, but it settles into steady operation. This shows good voltage regulation and dynamic performance of the proposed system/converter. Figure 17 shows the output voltage across the motor load of the resonant DC-DC converter with a π-filter for the closed-loop sliding mode controller system, and its value is 49V.

**Table 2:** Comparison of time-domain parameters of voltage reference

| Type of Controller | Tr (s) | Tp (s) | Ts (s) | Ess (V) |
|---|---|---|---|---|
| PID | 0.70 | 0.85 | 1.45 | 1.12 |
| SMC | 0.62 | 0.81 | 1.20 | 0.98 |

Figure 18 shows the output current through the motor load of the resonant DC-DC converter with a π-filter for the closed-loop sliding mode controller system; its value is 1A. Figure 19 shows the output power across the motor load of the resonant DC-DC converter with a π-filter for the closed-loop sliding mode controller system; its value is 48W.

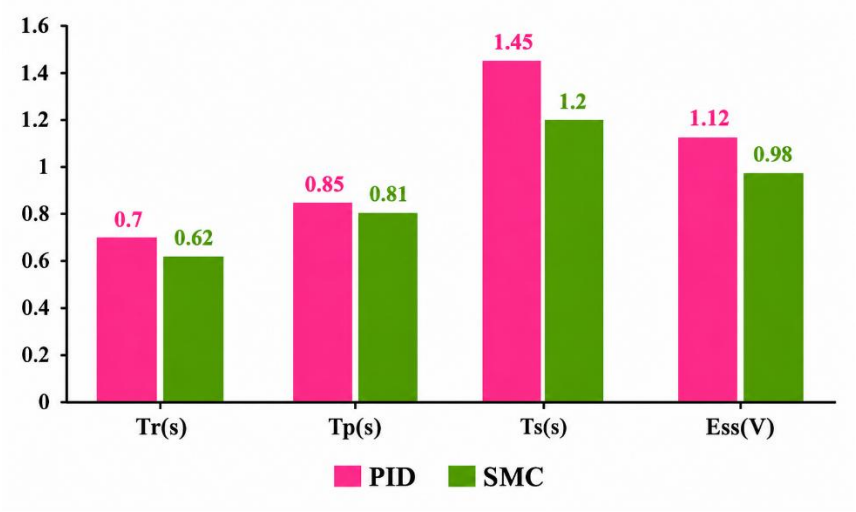



**Figure 20:** Bar chart comparison of time-domain parameters of voltage reference

Table 2 compares the time-domain parameters for the PID and SMC controllers of the proposed resonant DC-DC converter with a π-filter system. Figure 20 shows a bar chart comparing the time-domain parameters of the PID and SMC controllers for the proposed resonant DC-DC converter with a π-filter system. The SMC controller reduces the rise time from 0.7 s to 0.62 s.

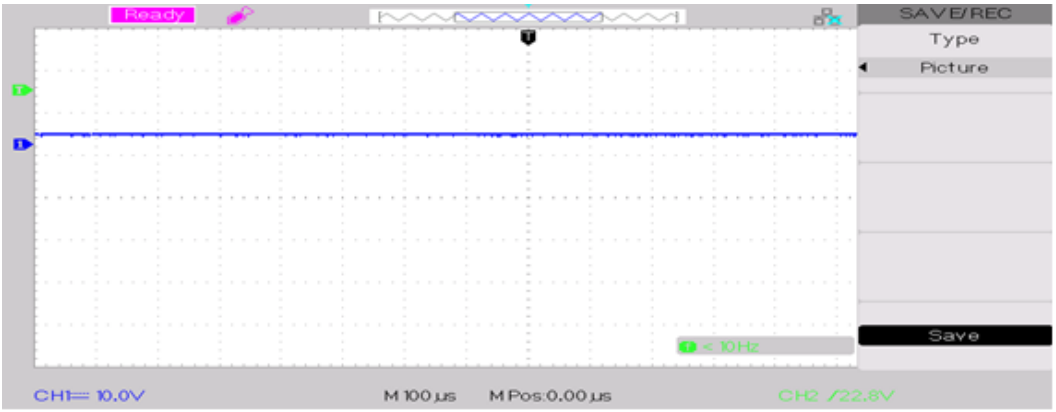



**Figure 21:** Input voltage

The SMC controller reduces the peak time from 0.85 s to 0.81 s. The SMC controller reduces the settling time from 1.45 s to 1.2 s. The SMC controller reduces the steady-state error from 1.12 V to 0.98 V. Thus, the results show that the closed-loop SMC controller outperforms the closed-loop PID controller for the proposed resonant DC-DC converter with a π-filter system.

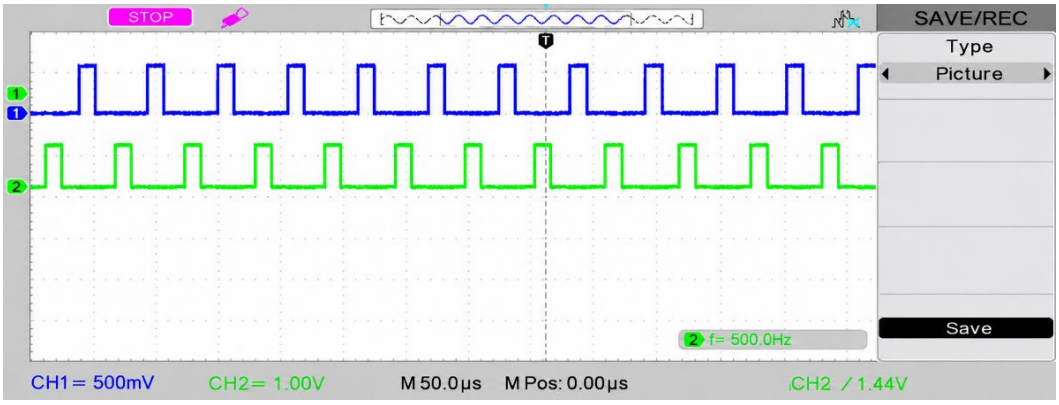



**Figure 22:** Switching pulse for M1, M3

Figure 20 shows a hardware snapshot of the resonant DC-DC converter with a π-filter. Figure 21 shows the input voltage of the resonant DC-DC converter with a π-filter; its value is 15V. Figure 22 shows the switching pulse for M3 for the resonant DC-DC converter; it switches M1 and M3.

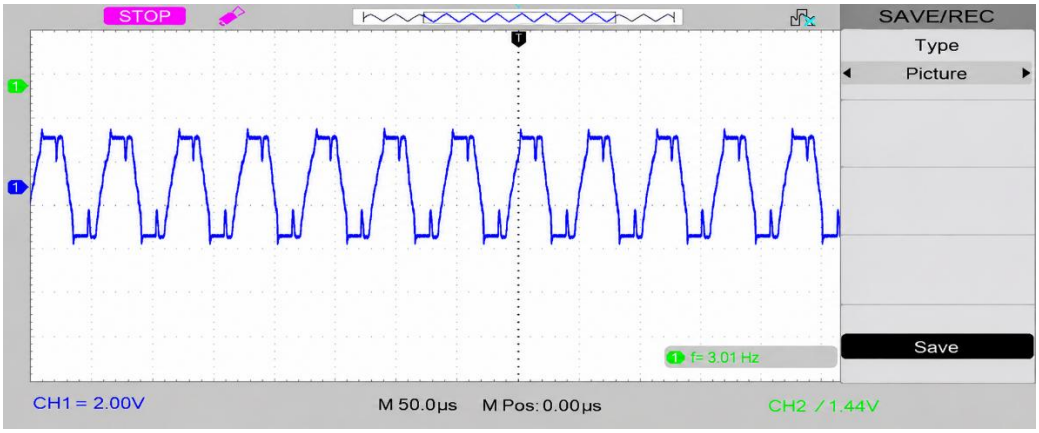



**Figure 23:** Transformer primary voltage

Figure 23 shows the transformer primary voltage, which is 15V.

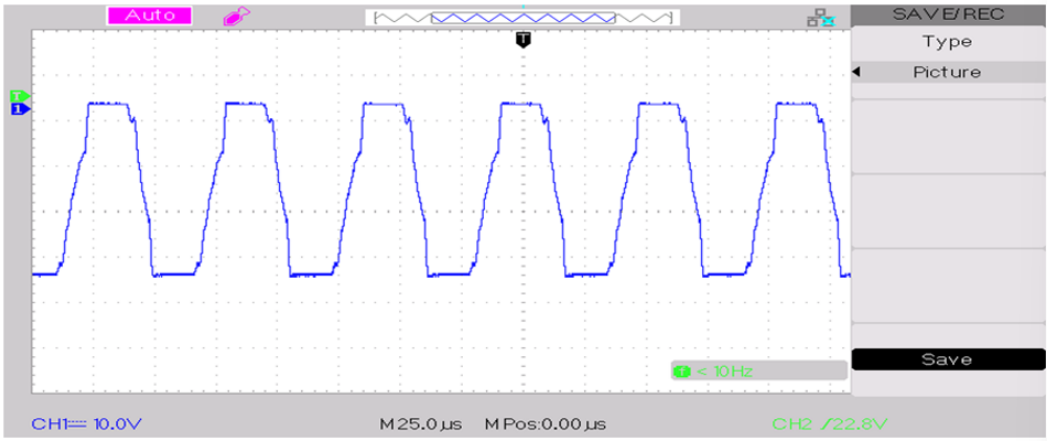



**Figure 24:** Transformer secondary voltage

Figure 24 shows the transformer secondary voltage, which is 48V.

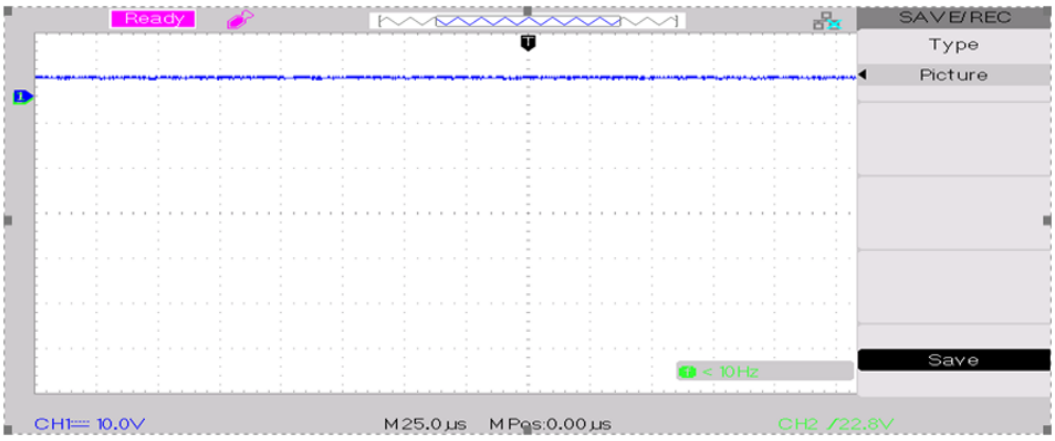



**Figure 25:** Output voltage

Figure 25 shows the output voltage of the resonant DC-DC converter 28, which is 45V.

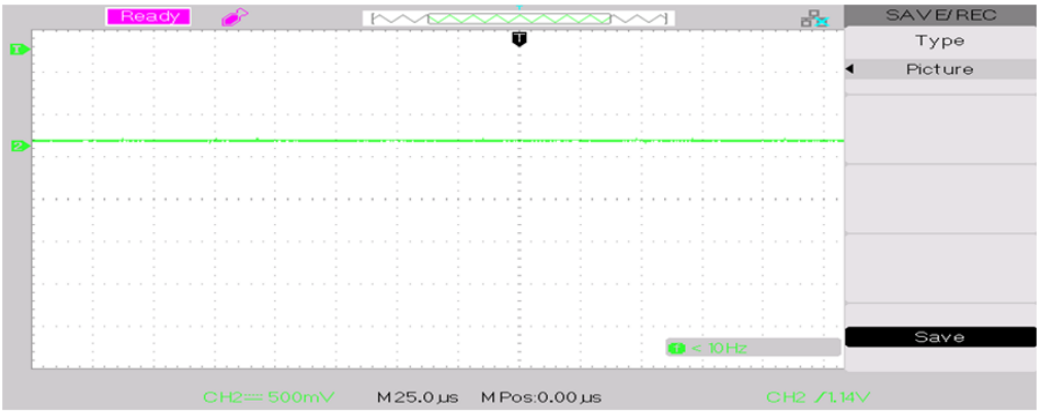



**Figure 26:** Output current

Figure 26 shows the output current of the resonant DC-DC converter, which is 0.9A (Table 3).

**Table 3:** Comparison of simulation and hardware results

| No. | Simulation | Hardware |
|---|---|---|
| 1 | PWM pulse from Simulink library | PWM pulse from PIC controller |
| 2 | Closed-loop system (PID/SMC) | Open-loop system |
| 3 | Input voltage = 15V | Input voltage = 15V |
| 4 | Output voltage = 48V | Output voltage = 45V |
| 5 | Output current = 0.97A | Output current = 0.9A |

## 5. Conclusion

We successfully modeled and simulated the proposed resonant DC-DC converter with a π-filter under open-loop and closed-loop operating conditions. Initially, the open-loop configuration with a source disturbance was studied to evaluate the converter's basic dynamic behavior and disturbance response. Later, we developed a closed-loop PID-controlled scheme to improve output-voltage regulation and dynamic performance. A closed-loop Sliding Mode Controller (SMC) was also designed to provide a robust, faster response under varying operating conditions. The performance of the two control strategies was evaluated using key time-domain parameters such as rise time, peak time, settling time and steady-state error. The simulation results show that the Sliding Mode Controller's dynamic performance is better than that of the PID controller. The rise time decreases from 0.70 s to 0.62 s with SMC implementation, indicating a faster response to changes in the reference input. The maximum time also decreases from 0.85 s to 0.81 s, indicating that the maximum response is reached faster. The settling time decreases significantly from 1.45 s to 1.20 s, indicating that the converter reaches its steady operating condition faster. Moreover, the steady-state error improves from 1.12 V to 0.98 V, indicating better output-voltage regulation and accuracy. Therefore, the results confirm that the closed-loop Sliding Mode Controller provides better transient and steady-state performance than the closed-loop PID controller for the developed resonant DC–DC converter with a π-filter. The improved response and reduced steady-state error indicate SMC's suitability for applications requiring fast, stable and robust DC–DC voltage regulation. Thus, the proposed SMC-based resonant converter is an effective solution for high-performance power conversion applications.

**Acknowledgment:** The authors sincerely acknowledge the support, resources, and academic contributions provided by Sumy State University, Cordoba Private University, Aleppo University, SRM Institute of Science and Technology at Ramapuram, EBLA Private University, and Pearl Harbour Manufacturing.

**Data Availability Statement:** The data supporting this study are available from the corresponding author upon reasonable request.

**Funding Statement:** This research was conducted without any financial support, grants, or external funding.

**Conflicts of Interest Statement:** The authors declare that there are no conflicts of interest regarding this work, and all sources have been appropriately acknowledged.

**Ethics and Consent Statement:** The study was conducted in accordance with applicable ethical guidelines, with informed consent obtained from all participants.

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