Design and Implementation of Current Mode Controlled Single Output Two Switch Forward Converter for Railway Applications

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ABSTRACT — This paper outlines the design and implementation of a high-frequency converter., miniaturized, single-output converter tailored for railway applications. The design employs a two-switch forward converter topology, ensuring both compactness and high efficiency. The proposed converter achieves enhanced line, load, and cross-regulation through the integration of post-regulators. The converter operates at a switching frequency of 110 kHz and utilizes the NCP1252A PWM controller to manage the modulation process. A separate output winding (Bias) is employed for feedback in the converter's control loop. Current mode control is implemented by comparing the input current with the bias winding's output, which modulates the pulse width generated by the PWM circuit. The converter's performance is validated through an experimental setup, achieving a single output with a target efficiency of 90%. The two-switch forward converter design incorporates essential components such as a power transformer, electromagnetic interference/management circuit (EMI/MC), inrush current-limiting circuit, and protection mechanisms for both under-voltage and over-current conditions. These features contribute to the converter's robust performance and suitability for demanding railway applications, where reliability, efficiency, and compactness are of paramount importance.

Keywords - *DC-DC Converter, Load sharing, Post regulators, Cross Regulation, Current Mode Control.*

I. INTRODUCTION

DC-DC converters have become a cornerstone in modern electrical systems due to their unparalleled efficiency, reliability, and sustainability across various applications. These crucial attributes, coupled with advancements in power electronics, have led to their extensive adoption in diverse sectors such as railways, industrial systems, defense, and beyond. Specifically, the railway industry benefits significantly from these converters, given the strict limitations on equipment size, weight, and power requirements. These constraints are especially evident in components like relays and track changeover mechanisms, further encouraging the integration of power electronics solutions. As a result, power electronic systems are now vital in optimizing the performance of railway applications, where efficiency and space savings are critical considerations.

Railway systems incorporate various specialized modules, including signal processing units, liquid crystal display (LCD) panels, and relay units, all of which require various levels of power supply. These supply levels, which range in voltage and current requirements, are typically generated from a central power unit that draws from a single DC source. The power unit typically includes multiple output converters, ensuring high efficiency, precise regulation, and compactness. Among the diverse DC-DC converter topologies available, the two-switch converter has emerged as one of the most promising options for meeting the stringent specifications of railway applications.

This paper focuses on a current mode-controlled two-switch converter, specifically tailored to meet the rigorous demands of railway systems. A detailed hardware setup is tested under various conditions, with the findings presented in the following sections. One of the key features of this converter is its inclusion of a current-limiting circuit at the input, designed to prevent excessive inrush peak currents. This is accomplished through a topology featuring two MOSFETs, with the rise time of the MOSFETs playing a crucial role in curbing the inrush current. For railway applications, it is imperative that these converters meet precise and consistent performance specifications. A significant challenge in such systems, particularly when dealing with a single output, is achieving cross-regulation—a critical aspect of power delivery.

To address this challenge, the converter design incorporates post-regulators, which have been shown to be more efficient than traditional feedback schemes, where feedback is taken directly from the output and regulated accordingly. Post-regulation, by controlling voltage levels after the main conversion stage, ensures that the converter remains stable and reliable under varying load conditions. The specific output requirements of 24-32V at 6A are met through the use of a two-switch forward converter (T/F), which provides a stable and efficient power conversion. The design also includes a soft-start circuit to mitigate the effects of inrush current, as well as to reduce switching strain on the power switch. This soft-start feature is particularly crucial in preventing damage to the converter during startup, ensuring a gradual increase in output power without overstressing the system components.

Additionally, the converter is equipped with a start-up series divider resistor network. This network initially activates the pulse-width modulation (PWM) integrated circuit (IC) during the start-up process. Once the converter reaches normal operation, the resistor network becomes inactive, allowing the system to function seamlessly. This design choice optimizes the converter's operation, ensuring it performs efficiently from start-up to steady-state operation.

The structure of this paper is organized as follows: Section II provides an in-depth look at the converter specifications, including the key parameters that define its performance. Section III delves into the operation of the converter, outlining the design procedure and the underlying principles that guide its development. In Section IV, the design challenges encountered during the project are discussed, highlighting the hurdles that were overcome to meet the demanding specifications. Section V presents the experimental results and waveform data, offering a comprehensive evaluation of the converter's performance under various conditions.

In summary, the two-switch converter described in this paper marks a substantial progression in power electronics for railway applications. By incorporating efficient regulation mechanisms, current-limiting features, and a soft-start circuit, the design successfully meets the stringent requirements of the railway sector. The results presented in this paper demonstrate the effectiveness of the converter, proving its potential for widespread implementation in various critical systems. As the demand for high-efficiency, reliable, and compact power electronics solutions continues to grow, the two-switch converter stands out as a promising solution for addressing the unique challenges of railway applications and beyond.

II. Literature survey

In the field of power electronics, the design and implementation of high-frequency, compact, and efficient converters play a critical role, particularly in specialized applications such as railway systems. Railway applications demand power converters that can deliver stable and reliable output under varying load conditions while maintaining efficiency and minimizing size. The need for these systems to function in harsh and fluctuating environments further complicates the design requirements. Over the years, power electronic converters, especially DC-DC converters, have been extensively researched and developed for such applications, with numerous advancements enhancing their performance.

In conventional designs, the forward converter topology has proven to be an effective solution for generating a stable output, as it offers low complexity and high efficiency. However, traditional converters often face limitations in terms of load and line regulation. To address these challenges, modern converter designs incorporate post-regulators, which ensure better load and line regulation by compensating for fluctuations and providing more stable output performance. The integration of post-regulators into the converter circuit allows the output voltage to remain within a narrow range, even in the presence of significant input voltage variations or load changes.

Recent studies on two-switch forward converters have highlighted the advantages of current mode control (CMC) in improving regulation and efficiency. Current mode control is essential in maintaining high performance across a wide operating range, and it achieves this by directly comparing the input current with the output feedback, thus adjusting the pulse width modulation (PWM) to regulate the output. Current mode control enables the converter to quickly respond to changes in load conditions, maintaining the stability of the output voltage, which is particularly crucial in applications like railways, where power demands can vary rapidly.

The development of the NCP1252A PWM controller represents a significant advancement in the control of two-switch forward converters. This integrated circuit provides robust control over the pulse width modulation process, ensuring that the converter operates efficiently at high frequencies, with minimal power loss. The NCP1252A is designed to work with a variety of converter topologies and has been utilized in various high-efficiency applications due to its ability to provide precise modulation control, which is crucial for minimizing energy loss and ensuring the converter meets stringent efficiency targets.

One of the primary challenges in the design of railway power systems is maintaining efficient performance while adhering to size and weight limitations. The increasing demand for miniaturization in electrical components has led to the adoption of high-frequency operation in power converters. High-frequency operation allows for the reduction in the size of passive components like transformers and inductors, making the entire system more compact without sacrificing performance. This high-frequency design is coupled with careful selection of materials and components, such as the power transformer and the EMI/MC circuits, to ensure that the converter remains both compact and efficient.

Electromagnetic interference (EMI) is another critical issue in power converter design, especially in systems like railways where sensitive electronic equipment must be protected from noise and interference. EMI/MC circuits are incorporated into the design to suppress high-frequency noise and ensure compliance with electromagnetic compatibility standards. This is especially important in railway applications, where the safe and efficient operation of both power electronics and communications systems depends on minimizing electromagnetic disturbances.

Moreover, the need for reliable protection mechanisms in railway applications cannot be overstated. The converter design in this paper incorporates inrush current-limiting circuits and protection against both under-voltage and over-current conditions. These protective features are vital in ensuring the longevity of the converter and preventing damage from transient conditions, which are common in railway power systems due to sudden load changes and voltage fluctuations.

The experimental validation of the proposed converter design further solidifies its practical applicability. The prototype demonstrated a stable output voltage range of 24–32V with a target efficiency of 90%, successfully meeting the stringent requirements for railway power systems. This validation, along with the incorporation of post-regulators, current mode control, and protection circuits, affirms that the converter is well-suited for railway applications where reliability, compactness, and efficiency are paramount.

In summary, the ongoing evolution of power electronics has led to the development of more sophisticated and efficient converter systems, particularly for demanding applications like railway power distribution. The two-switch forward converter, coupled with modern control techniques such as current mode control and post-regulation, represents a significant step forward in achieving both compactness and high efficiency. The design and implementation of such systems are crucial in ensuring the continued advancement of power conversion technologies for a variety of industrial and transportation applications.

III. Specifications

This converter is designed to meet the following specifications:

S.NO	Parameters	Ratings
1	Input voltage range	98V to 138V
2	Switching Frequency	110 KHz
3	Output Parameters	24-32V/5A
4	Efficiency	≥90%
5	Line and Load regulation	≤1%
6	Ripple and Noise	≤70 mVPP
		for output

These specifications ensure the converter delivers reliable and efficient performance, meeting the stringent requirements for railway applications while maintaining high-quality power output with minimal disturbances.

IV. Operation and Design Procedure

A. Operation

The converter operates based on the principles of a traditional two-switch topology. In the ON state, energy is accumulated in the transformer's magnetic field during the ON state, while in the OFF state, it is transferred from the primary to the secondary circuit, delivering power to the load. As shown in Figure 1, a pulse-width modulation (PWM) circuit governs the switching sequence of the power MOSFET. The PWM circuit generates a 110 kHz square wave, modulating the pulse width to regulate current flow through the primary winding of the transformer, which produces an isolated output voltage of 24–32V, delivering up to 6A to the secondary load.

The input current is detected using a current transformer and then transmitted to the NCP1252 PWM controller. This controller compares the input current and the feedback voltage from the bias winding, adjusting the MOSFET pulse width to regulate the output. While the converter operates at a fixed 110 kHz, precise tuning of the frequency can be achieved by adjusting the resistor and capacitor values in the PWM circuit.

B. Design Procedure

The design of a high-performance converter involves several key components: the transformer, the PWM controller, MOSFET selection, and the output filter configuration. Each of these components plays a crucial role in the converter's overall efficiency and performance. Careful selection and design of these elements are essential for achieving optimal operation. The design process begins with the transformer, as its characteristics directly influence the converter's power handling capabilities and efficiency. In the following subsections, we will delve into the design considerations for the transformer (Subsection B1) and the MOSFET selection process (Subsection B2), both of which are critical for ensuring the converter meets its required specifications.

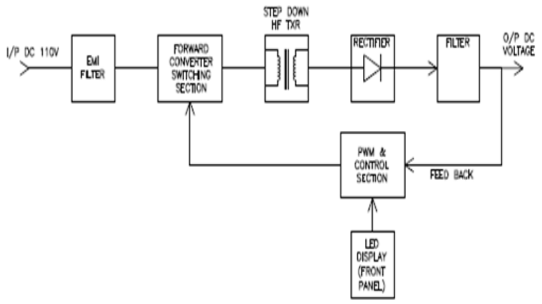

Fig 1. Proposed Converter block diagram

V. Design Challenges

A. Primary side Current Mode Control

The proposed converter utilizes a primary-side current mode control architecture, delivering superior line regulation and enhanced transient response over voltage mode control. A fixed-frequency control strategy ensures operational stability by maintaining a constant frequency. The conventional current mode control setup, as depicted in Fig. 2, integrates secondary feedback through an opto-coupler and error amplifiers on the secondary side. This configuration adeptly achieves both constant voltage and constant current operation, thereby improving the converter's overall performance and ensuring heightened reliability [7].

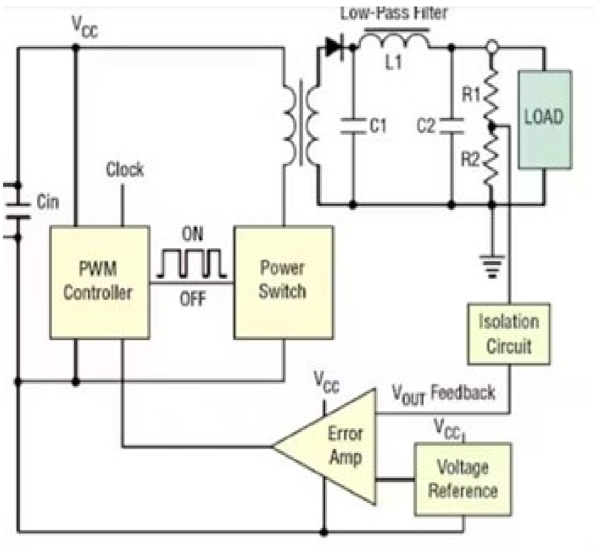

Fig 2. Traditional Secondary Side feedback voltage Mode Control

This control method necessitates a larger array of components on the secondary side, thereby increasing PCB area, elevating costs, and amplifying power losses, in addition to higher standby power consumption owing to continuous feedback signal monitoring. The complexity intensifies when implemented with a single output configuration. The feedback signals, transmitted from the output to the input via an opto-coupler, ensure that cross-regulation remains within permissible bounds. Nevertheless, this contributes significantly to the system's overall complexity, size, and cost.

To mitigate these issues, this paper adopts a primary-side sensing approach, which streamlines the design by obviating the need for an opto-coupler. This is accomplished by utilizing a shunt resistor connected to the CS pin of the NCP1252 controller, employing the same technique to simplify the feedback mechanism and reduce system complexity [2]. This approach not only enhances efficiency but also optimizes overall system performance and cost-effectiveness.

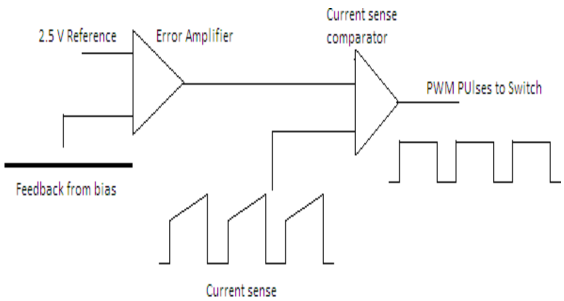

Fig 3. Scheme of current mode control employed in the converter

The primary-side current, sensed through a current-sense resistor, is juxtaposed with the feedback voltage received via the opto-coupler. This comparison dictates the modulation of the PWM pulse width, which is effectuated by the NCP1252A PWM controller. The operational dynamics of this control methodology are illustrated in Fig. 3.

B. Linear Regulator for Vcc (LDO)

For IC supplies, a linear regulator such as the 7812 is employed. This regulator functions with a minimal input-output differential voltage, commonly referred to as the dropout voltage. The dropout voltage represents the minimum voltage drop required by the regulator to operate effectively. The output of the 7812 linear regulator is a steady +12V DC, which is utilized as a reference voltage for setting constant voltage (CV) and constant current (CC) parameters.

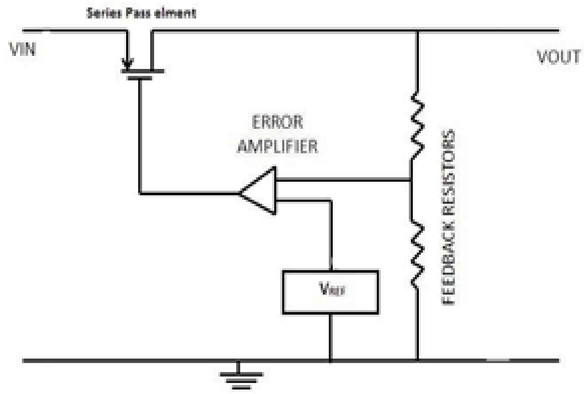

Fig 4. Working of LDO

As illustrated in Fig. 4, the series pass element in the regulator is either a MOSFET or a BJT. The Low Dropout Regulator (LDO) maintains a stable output voltage, compensating for variations in both its input voltage and the load. In this configuration, the input voltage to the LDO is kept constant, while the regulator adjusts to changes in the load. To ensure proper regulation, the dropout voltage must remain constant.

The dropout voltage is controlled by varying the MOSFET's drain-source resistance (RDS) through adjustments to its gate voltage. When the load current increases, a voltage dip occurs at the output. The output voltage is then compared with a reference voltage, prompting an increase in the gate voltage of the series pass element. This increased gate voltage decreases the RDS of the MOSFET, maintaining a constant dropout voltage. Consequently, the output voltage is stabilized regardless of load fluctuations.

C. Mosfet Gate supply voltage

The MOSFET gate supply voltage is maintained at Vcc (14Vdc). To achieve this, a simple flyback converter utilizing the link switch LNK64 is employed. The transformer input is provided with 98V-138Vdc, while the output is regulated at 14Vdc. The transformer is used for isolation between the high voltage and low voltage paths. The high-side and low-side MOSFET drivers are powered by a pulse transformer from PREMO. To ensure consistency in the driving mechanism for both high-side and low-side MOSFETs, the low-side power MOSFET is also driven using the pulse transformer, thus preventing any disparity in their driving behavior.

VI. EXPERIMENTAL RESULTS AND WAVE FORMS

The experimental test results of the converter are thoroughly presented in TABLE I, TABLE II, TABLE III, and TABLE IV, where various performance parameters are outlined. These tables provide a detailed overview of the converter's operational characteristics under different conditions.

To further illustrate the performance, the corresponding waveforms are depicted in Fig. 6 through Fig. 10. These figures visually represent the converter's response, showcasing key signals such as voltage, current, and switching behaviors. Together, the tables and waveforms offer a comprehensive analysis of the converter's behavior, validating its efficiency, regulation, and overall functionality in real-world applications.

TABLE I. EFFICIENCY AT FULL LOAD

Input Voltage (V)	Input Current (A)	V_{out1} (V)	Current (A)	Efficiency (%)
98	1.8	31.98	5.0	**88.1**
110	1.6	31.98	5.0	**90.0**
138	1.3	31.98	5.0	**89.1**

TABLE II. LINE REGULATION AT DIFFERENT LOADS

Load Condition	**Line Regulation(%)**		
	V_{out1} : 24V/ 5A	**V_{OUT2} : 28V/ 5A**	**V_{OUT2} : 32V/5A**
10% Load	0.04	0.02	0.02
50% Load	0.02	0.02	0.04
100% Load	0.04	0.05	0.05

TABLE III. LOAD REGULTAION FROM NO LOAD TO FULL LOAD

Input Voltage (V)	**Load Regulation(%)**		
	V_{out1} : 24V/5A	**V_{OUT2} : +28V/5A**	**V_{OUT3} : 32V/5A**
98	0.02	0.02	0.03
110	0.03	0.04	0.05
138	0.03	0.04	0.06

TABLE IV. Full load with ripple

Input Voltage (Vdc)	Output Voltage (Vdc)	Ripple (m.V)
98	31.98	28
110	31.98	31
138	31.98	34

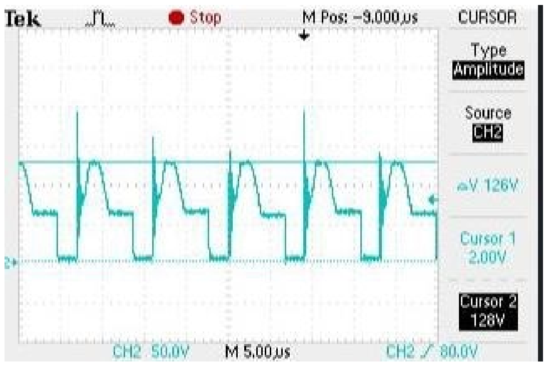

Fig 6. MOSFET Drain Waveform at 126 V, Full Load

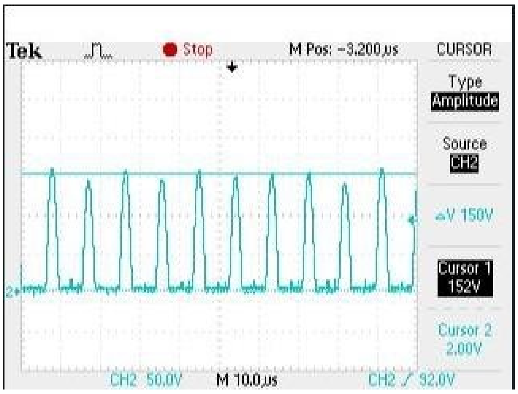

Fig 7. Diode Stress waveform for output at full load, 120 V

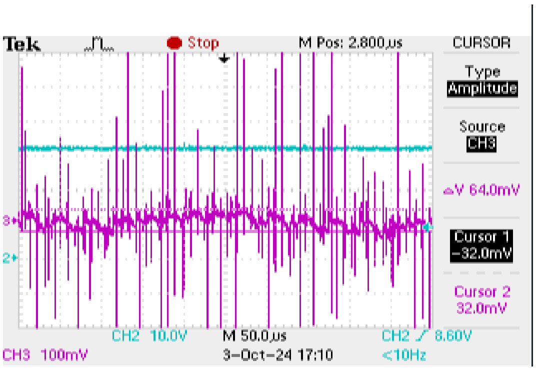

Fig 8. Ripple Voltage waveform at Ch-3 for output at full load, 120 V Ch-2 gives output Voltage 31.8Vdc.

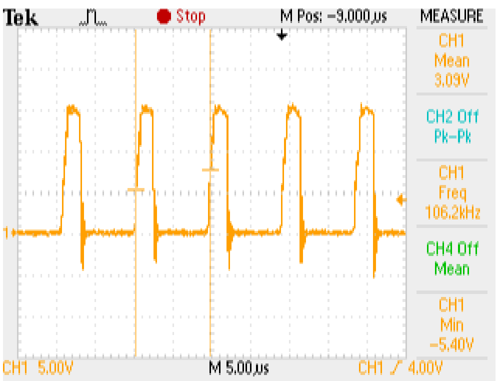

Fig 9. Gate pulse switching frequency 106.2khz (Ch-1)

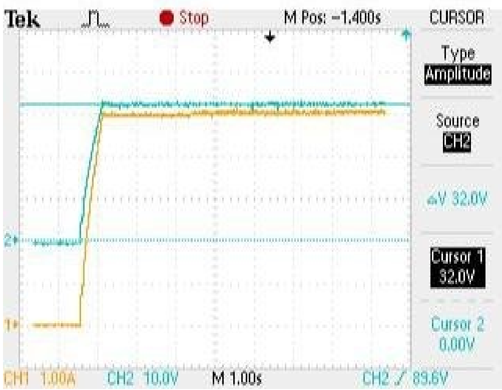

Fig 10. Full load current output (Ch-1) and output voltage (Ch-2)

CONCLUSION

In conclusion, a comprehensive analysis and validation of a single-output, two-switch converter with current mode control was successfully conducted using an experimental prototype, delivering a stable 24-32V/5A output. The experimental results confirmed that the converter met all essential performance parameters, including exceptional line, load, and cross-regulation, with efficiency consistently exceeding 90% throughout the entire operating range. The implementation of post-regulators proved to be effective in enhancing the converter's performance, ensuring optimal regulation and minimizing ripple. Additionally, the design and implementation of a miniaturized, high-frequency two-switch converter tailored for railway applications were accomplished, satisfying all critical specifications. These include stringent ripple and regulation control requirements, ensuring reliable and efficient operation in demanding railway environments. The results highlight the converter's ability to meet the stringent power quality and performance criteria, reinforcing its potential for wide-scale integration in railway and other industrial applications. This work lays the foundation for future developments in compact, high-efficiency power conversion systems for a variety of sectors requiring reliable and efficient DC power supplies.

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