RESEARCH ARTICLE

High-Voltage Power Supply: Design Considerations and Optimization Techniques

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Abstract

The main goal of this study is to design and develop a half-bridge inverter architecture specifically for high-voltage power supply applications. An effective, small, and affordable system that converts direct current (DC) to alternating current(AC) can be built, thanks to the IR2151 chip's dependable characteristics and performance. To get the desired output voltage, the transformer first increases the voltage and then the voltage is increased with a voltage-doubling rectifier (VDR) circuit. The study emphasizes how crucial it is to choose components carefully and simulate the circuit design and implementation process to guarantee dependable performance. The experimental results validate the suggested architecture's operational efficacy and viability. Moreover, the system's control mechanisms are strengthened by integrating Fractional Order PID (FOPID) and Proportional-Integral-Derivative (PID) controllers. These controllers provide vital feedback for stable output voltage and improved flexibility under transient situations. This study significantly advances the field by addressing key challenges such as size reduction, cost optimization, and improved control strategies, which are critical for high-voltage applications.

Keywords: high-voltage power supply, half-bridge inverter, IR2151 Chip, voltage doubling rectifier (VDR), DC to AC Conversion, circuit design and simulation, fractional order PID.

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1 Introduction

Power electronics rely heavily on designing and optimizing high-voltage power supply for various applications, such as renewable energy systems and industrial machines. The half-bridge inverter is one of the most popular topologies because of its versatility, dependability, and efficiency while handling high-voltage demands. Two switches linked in series over a direct current (DC) voltage source make up this inverter. By varying the output polarity,

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the midpoint between these switches serves as the output terminal and permits the creation of alternating current (AC) from direct current (DC) input [1, 2]. By varying the output polarity, the midpoint between these switches serves as the output terminal and permits the creation of alternating current (AC) from direct current (DC) input. To achieve the best performance, the design process necessitates carefully selecting components, such as Metal Oxide Field Effect Transistors (MOSFETs), insulated gate bipolar transistors. (IGBTs), gate drive circuits, and control techniques [2].

Recent research has looked into several approaches to high-voltage power supply design. For instance,one study generates the necessary power supply while enhancing cost-effectiveness via a flyback converter technique [3]. Another article offers comprehensive details on the implementation and technique of a high-voltage platform designed to investigate the switching characteristics of high-voltage (HV) power devices. Furthermore, studies on travelling wave power supplies emphasize the advantages of full-bridge converters, supported by computer simulations and theoretical analysis showing 97% device efficiency. One of the additional contributions is a resonant converter model that examines output gain in connection to capacitor ratios. The model's computational outcomes validate the design of the models [4].

With various note worthy breakthroughs, this research piece presents a substantial contribution to the field. It describes the development of a high- voltage power supply that can run at a frequency of20 kHz, representing a significant breakthrough in power electronics [5]. The IR2151-based half-bridge inverter integrated into the design improves system efficiency and performance [6]. The paper shows the simplified design, cutting costs and size using a voltage-doubling rectifier (VDR), VDR is a circuit that increases the output DC voltage to approximately twice the peak AC input voltage using capacitors and diodes [7]. To ensure accuracy in its execution, the article also offers comprehensive computations of the prototype's component values [8]. The suggested design's adaptability to different input voltages renders it highly adaptable and appropriate for an extensive array of applications [9]. Finally, the concept effectively achieves an outstanding 2080V output voltage, demonstrating its usefulness in high-voltage applications [10].

Integration of safety features such as over voltage protection and current limiting mechanisms to safeguard both the circuit and connected devices. Moreover, this study incorporates Proportional Integral Derivative (PID) control strategies and fractional-order PID controllers to enhance system stability and response time. The proposed system aims to achieve superior performance metrics by implementing these advanced control techniques, ensuring precise voltage regulation and improved transient response in high-voltage applications [9, 10].

This paper is ordered as follows: Section 1 defines the introduction. Section 2 describes the recent trends in this field. In section 3, the problem statement with the proposed solution is presented. In section 4, the power supply design is offered. Section 5 represents the design of the Power Transformer. Section 6 demonstrates the Voltage Doubling Rectifier (VDR) Circuit. Section 7 delivers the experimental results. Finally, the conclusions of this paper are drawn in section 8.

2 Related Work

This portion of the paper focuses on current high-voltage power supply design developments. This study develops a power supply using output series and input parallel converters. Using optimal control strategies that ensure no output ripples, this system combines feed-forward and feedback control mechanisms to provide exact regulation. The success of the suggested power supply is confirmed by the division of the input and output portions, which guarantees that changes in one do not adversely affect the operation of the other [11].

This work designs and tests a prototype high-voltage pulse power supply with an energy storage capacitor bank to allow for extensive testing and optimization. The system's robustness and adaptability for optimization are increased by continuously monitoring output parameters and storing data for additional study. This design successfully satisfies every criterion that was given [12].

In addition, it presents a high-voltage pulse power supply that operates at high frequencies and is modeled after the Marx circuit. The system transmits messages via optical fibre and then sends those signals to the MOSFETs via a transformer. This configuration results in a simpler and more efficient circuit design, achieving an output voltage of these control techniques with in the design of 10 kV from an input of 630V.

Lastly, it presents a high-precision voltage power supply capable of delivering a maximum output voltage of 3 kV at 5 mA. The system exhibits excellent load regulation, line regulation, and minimal output voltage ripples. Simulations conducted on the power supply validate its accuracy, and the fabricated prototype confirms that it meets all required specifications [13]. Integrating advanced control strategies such as PID controllers and Fractional Order PID (FOPID) controllers is essential to enhance the performance of these high-voltage power supplies. The PID controller provides robust feedback for maintaining desired voltage levels, while FOPID controllers offer improved transient response and stability due to their incorporation of fractional calculus principles. This allows for a better representation of system dynamics, particularly in systems with non-integer dynamics or time delays. By implementing a framework, the stability and efficiency of high-voltage power supplies can be significantly improved, ensuring reliable operation across various applications [14].

3 Problem Statement

Half-bridge inverters are used in the suggested designs for high-voltage power supplies because they are inexpensive, small, and reasonably priced. The primary issue is creating a plan that efficiently translates input voltages, enhances them with a transformer, and produces the required high-voltage output. Voltage sags, surges, spikes, electrical noise, and frequency drift are common issues with power supplies. Moreover, it is imperative to integrate safety protocols and provide flexibility in response to varying input voltages. This work offers a unique and affordable high-voltage power source that addresses these issues using an IR2151-driven half-bridge inverter. Optimizing component selection and circuit architecture aims to achieve the intended output while maintaining crucial performance parameters. Precision control is made possible by the IR2151 chip, which reduces power losses and boosts efficiency. A voltage doubling rectifier (VDR) converts the transformer's output into a higher DC voltage. The system's ability to maintain steady output voltage levels even in the face of changing input conditions is enhanced by the integration of proportional-integral-derivative (PID) control techniques. The PID controller guarantees dependable and consistent performance by efficiently lowering steady-state error and overshoot. Further benefits come from using Fractional Order PID (FOPID) controllers, which allow for more precise modifications to the system's dynamics via fractional calculus. This feature improves stability and transient response, particularly in systems where conventional PID control might not be adequate. Safety measures are implemented to protect the circuit and the attached devices, such as current limiting systems and over voltage protection. Additionally, adaptable to accommodate a range of input voltages, the suggested design increases its suitability for various uses. The system design process is illustrated in Figure 1, which provides an overview of the workflow, outlining the essential components and control mechanisms implemented to ensure a stable and efficient high-voltage power supply.

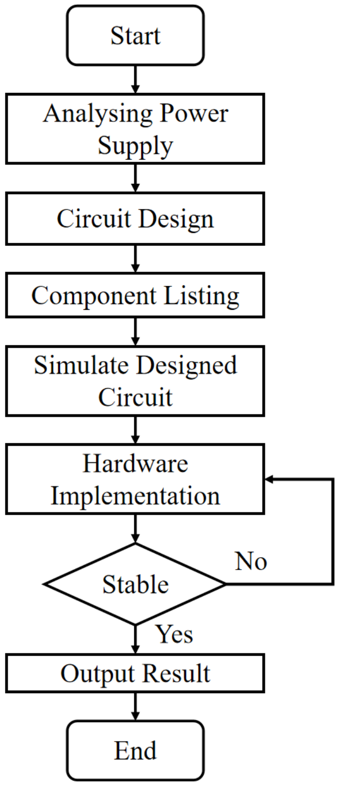

Figure 1. Work Flow Diagram.

4 Designing of High Voltage Power Supply

Three essential procedures are used to design the suggested high-voltage power supply. Initially, a half bridge inverter controlled by the IR2151 micro processor converts a 12V DC input voltage into a ±6V AC square wave. A transformer then steps up this AC square wave to 416V, and a voltage-doubling rectifier circuit converts it into a high-voltage DC output of 2.1kV.

PID and FOPID controllers are crucial to enhancing the power supply's stability and performance. To

Table 1. Comparison of High-Voltage Power Supply Designs and Control Strategies.

Feature / Parameter	Design 1: Output Series and Input Parallel Converters	Design 2: High-Voltage Pulse Power Supply with Capacitor Bank	Design 3: High-Frequency High-Voltage Pulse Power Supply	Design 4: High-Precision Voltage Power Supply (3kV, 5mA)
Control Strategy	Feed-forward and feedback control for exact regulation	Data monitoring for optimization	Optical fibre signal transmission; MOSFET control through the transformer	Proportional-integral-derivative (PID) and Fractional Order PID (FOPID) controllers
Output Voltage	Regulated with no output ripples	Varies depending on testing and optimization	10 kV from 630 V input	3 kV at 5 mA
Load Regulation	Ensured by separation of input and output sections	Robust; adaptable through real-time monitoring	Simplified design using MOSFETs and optical fiber	Excellent load regulation
Line Regulation	Not explicitly mentioned	Adaptable through continuous output monitoring	Not explicitly mentioned	Excellent line regulation
Efficiency	High due to optimal control	Improved by extensive testing and energy storage	Simplified and efficient circuit design	High, with minimal voltage ripples
Validation Method	Simulation and analysis	Prototype testing and data collection	10 kV output achieved from 630V input	Simulation and prototype validation
System Robustness	Input and output independence	Increased through continuous monitoring and adaptability	Simplified design improves robustness	Improved by FOPID controller integration
Reference	[11]	[12]	[13]	[14]

efficiently reduce fluctuations brought on by load or input variations changes, the PID controller provides robust feedback for maintaining stable output voltages. FOPID controllers, on the other hand, offer more flexibility in systems with intricate dynamics since they allow for fractional tweaking of the integral and derivative terms.

This feature enhances transient behavior and reduces overshoot, enabling more exact control over system reactions. Deploying these sophisticated control techniques can significantly lessen common problems like voltage sags and spikes in high-voltage applications where accuracy is essential. A comparison of different high-voltage power supply designs and their control strategies is provided in Table 1, highlighting the trade-offs between regulation methods, efficiency, and system robustness. By applying FOPID approaches to optimize the control parameters, the system can achieve enhanced load regulation and ripple reduction performance.

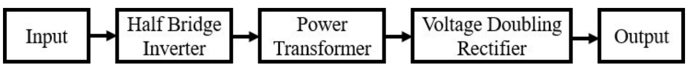

Figure 2. Block Diagram of System.

Figure 2 represents the block diagram of the system. Safety measures such as current limiting and over voltage protection are also crucial to the design to safeguard the circuit and the attached devices. The suggested design's adaptability allows it to function dependably in various applications while supporting a range of input voltages. To sum up, the combination of sophisticated control techniques like PID and FOPID with sturdy circuit design enhances the effectiveness and stability of high-voltage power supplies, while two MOSFET transistors and a half-bridge control chip make up the majority of the IR2151 half-bridge inverter circuit arrangement. When the system is first powered on, the IR2151 chip's pins 5 and 7 produce a square wave signal, alternating at a 50% duty cycle. This square wave is essential to drive the MOSFETs and enable effective switching and energy conversion.

Adding Fractional Order PID (FOPID) and Proportional Integral Derivative (PID) controllers can significantly increase this inverter circuit's performance. The PID controller provides Strong feedback control, which guarantees that the output voltage will not fluctuate regardless of changes in the load or input conditions. It improves overall system responsiveness and successfully lowers steady-state error. FOPID controllers, on the other hand, use fractional calculus to improve the capabilities of conventional PID control. With more accurate adjustment of the integral and derivative actions made possible, systems with complicated dynamics, such as those in high-voltage applications, may exhibit improved transient response and stability. Fractional order adjustments enable better control overnon-linearities and time delays that may occur during operation. By incorporating these sophisticated control techniques, the IR2151 half-bridge inverter circuit can regulate the output voltage more effectively and lessen oscillations and voltage spikes. In applications involving high-voltage power supplies, accuracy and dependability are crucial.

To summarize, the combination of the PID and FOPID control approaches, and the robust architecture of the IR2151 not only improves the inverter's performance but also makes it more adaptable to changing operating situations, making the high-voltage power supply system more dependable and efficient.

5 Power Transformer Design

Selecting the appropriate iron core materials for switching power supply transformers is crucial to improving efficiency and performance. Soft magnetic ferrite is a material that is frequently utilized because of its high resistivity, affordability, and efficiency in high-frequency applications [15]. Its oxidation susceptibility, however, could shorten its life span and affect how well it functions in some conditions. Because of its well-suited qualities for applications requiring magnetic solid performance, Bomo alloy is particularly effective for flyback converter transformers due to its high magnetic flux density and permeability. High resistivity and saturation magnetic density of amorphous alloys are advantageous in reducing core losses. Their ability to transmit energy efficiently during high-frequency operations makes them an excellent option for switching power supply applications in the present era [16]. The design concept chooses soft magnetic ferrite PC40 as the transformer's core material after examining the properties of these materials. This decision was made due to its advantageous characteristics, which enhance power supply design performance and efficiency. These characteristics include high resistivity, reduced core losses, and appropriateness for high-frequency applications. This choice is driven by its favorable attributes, which include easy wiring, plenty of winding area, and small size, which makes it ideal for high-voltage power supply. Fractional Order PID (FOPID) and Proportional-Integral-Derivative (PID) controllers should be incorporated to enhance the power supply's performance. PID controllers effectively control the output voltage by providing feedback to counter act variations in input conditions or load [17]. Comparatively, because of their fractional tuning capabilities, FOPID controllers offer greater flexibility and allow for more accurate modifications to both integral and derivative actions.

The area product (AP) method and geometric parameter approaches are two techniques used to determine the size of magnetic cores. High-voltage power supply can have much higher over all efficiency, reliability, and steady performance for various applications by optimizing core design with modern control algorithms like PID and FOPID.

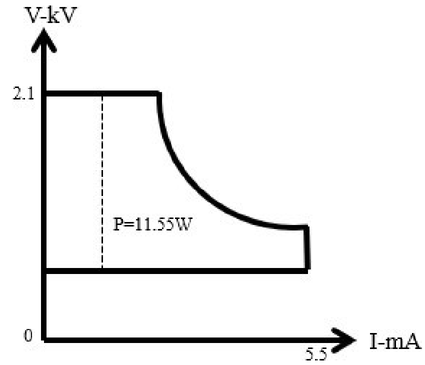

Figure 3. Output Voltage Vs. Current.

The switching power supply's design incorporates a number of characteristics to improve performance. The current output is at 5.5mA, with a power output of $P_0 = 11.55, WP_0 = 11.55W$. The relationship between output voltage and current is depicted in Figure 3, illustrating the performance characteristics of the designed transformer under varying load conditions. Based on the calculations provided, the are a product APAP is determined to be 1.17 cm 21.17cm^2 as per the equation:

$$A_p = A_w \times A_e = \frac{P_T \times 10}{K_u \times f_s \times \Delta B \times J} \tag{1}$$

where $J = 4\,\mathrm{A/cm^2}$ represents the current density, the DC voltage through the inverter is given as $V_{in} = 12\,\mathrm{V}$. The relationship between the areas can be expressed as:

$$A_w \times A_e = \frac{P_0}{12K_u \times f_s \times \Delta B \times J(y+1)} \tag{2}$$

To calculate the number of turns in the primary winding, we use:

$$N_p = \frac{V_{in} \times D}{\Delta B \times f_s \times A_e} \tag{3}$$

The duty cycle D is set at 0.5. The wire diameter can be calculated from the current density using:

$$D = \sqrt[2]{\frac{I}{\pi K}} \tag{4}$$

Where I is the current and K is a constant related to material properties. Integrating fractional order PID (FOPID) and Proportional-integral-derived (PID)

Table 2. Power Transformer.

Parameters	Values
K_s	0.2
f_s	12KHz
ΔB	0.3

controllers enhances system control. By adjusting for variations in input and load, the PID controller can efficiently maintain output stability. However, because of their tunable fractional orders, FOPID controllers are more flexible, enabling more accurate control over the dynamics of the system and faster reaction times in the event of brief occurrences. The key design parameters for the power transformer, including switching frequency and magnetic flux density, are summarized in Table 2.

Additionally, a "sandwich" winding technology is used, which strategically layers the primary and secondary windings to reduce leakage and control temperature increases in transformer windings. This design choice enhances the transformer structure's heat management using the best available space.

6 Voltage Doubling Rectifier (VDR) Circuit

The circuit depicted in Figure 4, the voltage-doubling rectifier, is necessary to generate high output voltages from low input levels. This circuit uses capacitors and diodes to convert the peak AC voltage into a larger DC voltage to double the input voltage effectively. A voltage-doubling circuit's ability to generate significantly higher voltages without requiring components with high voltage ratings is one of its key advantages; this increases cost-effectiveness and stream lines the design.

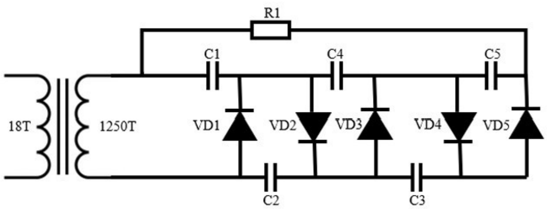

Figure 4. Schematic Diagram of VDR Circuit.

Operational requirements are satisfied by the high-voltage power supply's maximum total power output of 10 W in this arrangement. Following the power converter's boost effect, the transformer's secondary winding generates an AC square wave voltage of ±416 V. The Walton Voltage Doubling Circuit, renowned for its efficiency in generating large DC voltages, is incorporated in to the design [16, 17].

Fractional Order PID (FOPID) and proportional integral Derivative (PID) controllers can be integrated to improve the rectifier circuit's performance. Even in the presence of changes in the load or input circumstances, the PID controller can provide precise feedback control to guarantee consistent output voltage levels. This stability is essential in high-voltage applications requiring a steady output [18]. By allowing fractional adjustment of integral and derivative actions, FOPID controllers improve upon the features of conventional PID control. Because of its flexibility, the system's dynamics may be more precisely controlled [19–21], improving transient response and lowering overshoot during voltage changes.The voltage-doubling rectifier circuit's total performance can be significantly increased by incorporating these sophisticated control techniques, guaranteeing dependable operation in various applications [22–25].

In conclusion, the combination of a well-designed voltage-doubling rectifier circuit and advanced control techniques like PID and FOPID not only in conclusion, combining sophisticated control methods like PID and FOPID with a well-thought-out voltage-doubling rectifier circuit maximizes output efficiency while enhancing stability and dependability in high-voltage power supply systems. The voltage-doubling rectifier circuit produces high output voltages from lower input voltages through diodes and capacitors. Diode VD1 becomes conductive during the positive half-cycle of the secondary voltage of the transformer, allowing current to flow and charging capacitor C1. VD1 ceases conducting when the voltage reaches the negative half-cycle, whereas VD2 activates and charges capacitor C2. The input voltage is doubled because the voltage across C2 equals the sum of the secondary voltage and the charge from C1. Capacitor C4 charges to 3V as the cycle enters the subsequent positive half-cycle, while capacitor C3's value is raised to 4V by the transformer. Ultimately, capacitor C5 achieves a voltage of 5V, resulting in an output voltage of 2080V. The simplicity of the voltage-doubling rectifier (VDR) circuit makes it straight-forward to implement. Issues like charge leakage in capacitors and forward voltage dips across diodes can impact performance. Under load conditions, voltage drop is significantly affected by voltage doubling and can be computed using the following formula:

$$\Delta U = \frac{I(4N^3 + 3N^2)}{6fC} \tag{5}$$

where, N represents the order of the circuit, C is the capacitance, and f is the switching frequency. Additionally, output voltage ripple Up can be calculated with:

$$U_p = \frac{NI(N+1)}{4fC} \tag{6}$$

A 0.01 μF high-voltage ceramic capacitor that can tolerate up to 12 kV is used in this design to improve performance, meet with stand requirements, and minimize output ripple. The 2CL69 high-voltage diode model, with a maximum with stand voltage of 4 kV and a recovery time of 100 ns, is the model used. Circuit performance can be enhanced by combining Fractional Order PID (FOPID) with Proportional Integral Derivative (PID) controllers. By adapting toload or input conditions changes, the PID controller efficiently controls output voltage and ensures steady operation. FOPID controllers, on the other hand, allow for the fractional tuning of control parameters, providing better transient response and increased adaptability during abrupt changes in input or load. The overall efficiency and reliability of the VDR circuit design can be significantly improved by incorporating these sophisticated control strategies. This integration reduces possible voltage drop and ripple effects problems, and reliable performance from a high-voltage power supply is ensured.

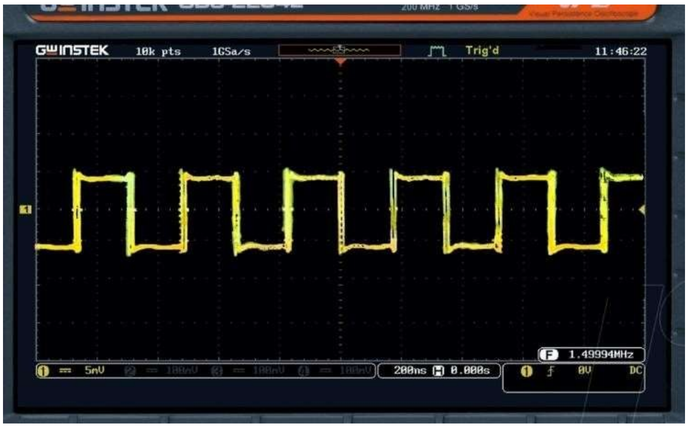

Figure 5. Half Bridge Inverter Output Waveform.

Figure 6. Transformer Output Waveform.

7 Experimental Verification

With notable gains instability and efficiency, the high-voltage power supply—based on a half-bridge inverter has effectively achieved its performance objectives. The leading causes of these improvements are focused optimization initiatives, like sophisticated component selection and switching techniques. The power supply performed admirably in various operating conditions, displaying minimal ripple and attaining precise voltage regulation.

As seen in the output waveform in Figure 5, the system converts a 12V DC input into a $\pm$6V AC square wave with a frequency of 20 kHz. Figure 6 displays the wave form that is produced following the half-bridge inversion technique. This design would not function without the voltage-doubling rectifier (VDR) circuit, effectively boosting the AC voltage to provide more significant DC output levels.

Fractional Order PID (FOPID) and Proportional Integral Derivative (PID) controllers must be incorporated to enhance this power supply's performance. The PID controller can provide accurate feedback to guarantee consistent output voltage even when input conditions or load fluctuate. This is particularly important for high-voltage applications where precision is crucial. Further advantages of the FOPID controller include the capacity to tune control parameters fractionally, improving transient response and adaptation to changing operating dynamics.

The VDR circuit's architecture minimizes output ripple while guaranteeing that high-voltage capacitors and diodes meet stringent with stand specifications. The 2CL69 high-voltage diode, which has a maximum withstand voltage of 4kV and a recovery time of 100ns, is utilized explicitly in conjunction with a high-voltage ceramic capacitor rated at 0.01 μF, capable of with standing up to 12kV.

By integrating these sophisticated control techniques into the entire design framework, the high-voltage power supply improves reliability and stability in various applications while simultaneously achieving optimal operational efficiency. This integration allows the system to manage voltage variations and maintain steady operation under different load scenarios.

The device receives a 12V DC input voltage, transforming in to a 2.1kV high-voltage output. Figure 7 displays the output wave form that corresponds to this acquired voltage. This significant voltage rise demonstrates the design's ability to convert low input voltages into high output levels, which is crucial for various high-voltage applications.

Figure 7. Module Output Voltage Waveform.

The simulations were conducted using MATLAB/Simulink to analyze circuit performance and validate the design, while the physical experimental setup utilized the IR2151 driver, high-voltage transformer, and voltage-doubling rectifier (VDR). Output voltage stability was monitored using an oscilloscope, and control mechanisms were implemented via FOPID and PID controllers for feedback and transient analysis.

8 Conclusion

This study's high-voltage power supply (HVPS) significantly increases work efficiency and power density by operating at 20kHz. Initially, the system uses a half-bridge inverter circuit driven by the IR2151 chip to transform a 12V DC input into a $\pm$6V rectangular voltage. A transformer is then used to boost this voltage to 416V, and after that, a voltage-doubling rectification circuit amplifies it even further, producing a high-voltage output of 2.1kV DC. Integrating fractional order PID (FOPID) and Proportional-integral-derived (PID) controllers is essential to improving the HVPS's stability and performance. PID controllers are necessary for high-voltage applications that demand accurate voltage regulation because they efficiently control the output voltage and compensate for variations in load or input circumstances. FOPID controllers, on the other hand, allow for fractional tuning of control parameters, which enhances transient response and flexibility in the face of abrupt operational changes.

The half-bridge inverter can be switched on and controlled effectively thanks to the IR2151 chip, which is essential to this design. It is perfect for driving MOSFETs or IGBTs due to its high-speed operation and suitability for high-voltage applications. Combining these sophisticated control algorithms with the sturdy HVPS design guarantees dependable performance in many load conditions. This makes the system suitable for applications that need accurate high-voltage outputs.

Conflicts of Interest

The authors declare no conflicts of interest.

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