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SIMULATION-DRIVEN COMPARATIVE EVALUATION OF POWER ELECTRONIC CONVERTERS: ANALYZING DIODE, THYRISTOR, AND IGBT-BASED PWM TOPOLOGIES ACROSS DIVERSE LOAD CONDITIONS USING HARMONIC, RIPPLE

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ABSTRACT:

This paper presents a comprehensive comparative analysis of three distinct power electronic converter topologies—full-wave diode rectifier, thyristor-controlled rectifier, and IGBT-based converter with PWM control—when operating under different load conditions. The primary objective was to evaluate and quantify the performance disparities between these converters when supplying resistive, inductive, and capacitive loads. Using a three-phase sinusoidal source (50 Hz, 100 V amplitude), each converter's response was simulated through numerical methods. Performance metrics such as ripple factor, harmonic content, and output stability were systematically assessed through time-domain waveform analysis, FFT spectral evaluation, statistical distributions, and comparison charts. Results demonstrate that while diode rectifiers offer simplicity and thyristor-controlled rectifiers provide basic control capabilities, the IGBT-based converter consistently outperformed the others across all load types, exhibiting the lowest ripple factors and harmonic distortion. For resistive loads, the IGBT converter produced stable output voltage with minimal fluctuations. With inductive loads, it provided smooth current transitions, effectively mitigating the integration effects. For capacitive loads, it demonstrated superior voltage stability with the narrowest statistical distribution. The frequency-domain analysis further confirmed the IGBT converter's advantage, showing significantly reduced harmonic components compared to the other topologies. This research provides valuable insights for power electronic system designers, particularly for variable frequency drive applications where power quality and load stability are paramount. The findings conclusively establish that despite higher complexity, IGBT-based converters represent the optimal choice for modern industrial applications requiring precise power management and high-quality conversion.

Keywords: *Power electronics, IGBT converter, Thyristor converter, Diode rectifier, PWM control, Harmonic analysis, Ripple factor, Variable frequency drives, Power quality, Load effects.*

1. INTRODUCTION

Power electronic converters are the foundational components that drive the efficiency and reliability of modern industrial systems, enabling the precise control and conversion of electrical energy for a broad spectrum of applications. The rapid advancements in semiconductor technologies, particularly in switching devices, have led to the evolution of a variety of converter topologies, each offering unique advantages in terms of control sophistication, power quality, and operational flexibility. Among these, three-phase converters are of paramount importance in critical industrial drive systems, renewable energy integration, power conditioning, and other energy-intensive applications, where the interaction between converter performance and load characteristics is central to system stability and efficiency.

This research delves into a comparative analysis of three widely used converter topologies: the full-wave diode rectifier, the thyristor-controlled rectifier, and the IGBT-based converter with Pulse Width Modulation (PWM) control. While each topology brings a different set of strengths, they cater to different operational needs. Diode rectifiers, for instance, are valued for their inherent simplicity and robustness, offering a reliable solution in applications where advanced control is not required. In contrast, thyristor-controlled rectifiers introduce basic yet effective control mechanisms through firing angle adjustment, allowing for moderate regulation of power flow.

On the other hand, IGBT-based converters, driven by sophisticated PWM techniques, provide the highest level of control and flexibility, enabling precise, dynamic power management that adapts to varying load conditions.

However, the interaction between a converter and its load is far from straightforward. The nature of the load—whether resistive, inductive, or capacitive—plays a crucial role in shaping the converter's behavior. These load types influence key performance parameters, such as output voltage stability, ripple factors, and harmonic distortion, which directly impact the efficiency and longevity of industrial systems. As power electronic systems are expected to operate under increasingly diverse and demanding conditions, understanding how different converter topologies respond to these varying loads is essential for the optimization of system performance and power quality.

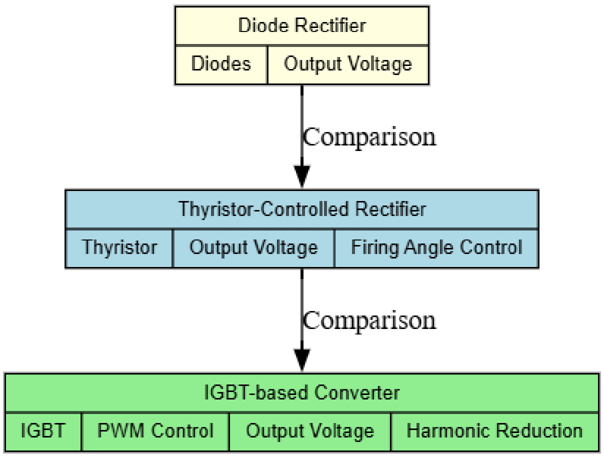

Fig Comparison of Power Electronic Converter Topologies

While there exists an extensive body of work on the individual characteristics of each converter topology, there is a noticeable gap in research that provides a comprehensive, comparative analysis under diverse load conditions. The majority of existing studies focus on specific topologies or idealized conditions, often neglecting the complex interplay between converters and real-world load profiles. This study aims to fill that gap by offering an in-depth evaluation of the performance of full-wave diode rectifiers, thyristor-controlled rectifiers, and IGBT-based converters when supplying resistive, inductive, and capacitive loads.

Through advanced numerical simulations and extensive performance analysis, this paper systematically examines critical metrics such as ripple factor, harmonic distortion, and output voltage stability. We aim to quantify how each converter topology behaves under different load types, providing engineers and designers with actionable insights that can guide the selection of the most appropriate converter for specific applications, particularly in systems where power quality is a key concern, such as Variable Frequency Drive (VFD) systems. These systems are crucial for optimizing the performance of motors, minimizing energy consumption, and extending the lifespan of equipment, making the selection of the right converter topology a matter of both operational efficiency and cost-effectiveness.

2. PROBLEM STATEMENT

Modern industrial systems require highly precise power control and superior electrical quality to maintain operational reliability and energy efficiency. Despite advancements in power electronics, selecting the most suitable power converter topology continues to pose significant challenges. This is largely due to the wide variation in load requirements across industrial applications, which may involve purely resistive loads or complex combinations of inductive and capacitive elements. Furthermore, there is a scarcity of quantitative data that directly compares the performance of different converters across various load types. A limited understanding persists regarding the influence of load characteristics on converter behavior, particularly in relation to ripple factor and harmonic distortion. Compounding the issue is the absence of standardized metrics to evaluate converter performance under varying operating conditions. Although advanced converters, such as those based on Insulated Gate Bipolar Transistors (IGBTs), are widely regarded for their qualitative benefits, there is often insufficient quantitative evidence to substantiate their superior performance for specific load scenarios. This lack

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of concrete data complicates cost-benefit analyses, thereby hindering informed decision-making by system designers.

3. RESEARCH OBJECTIVES

The primary objectives of this research are:

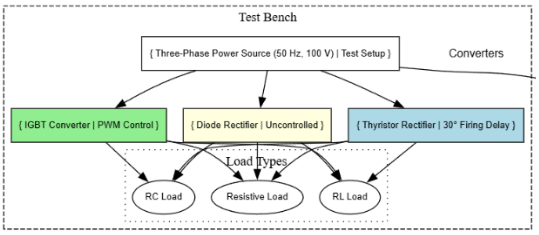
1. To quantitatively compare the performance of three distinct converter topologies—full-wave diode rectifier, thyristor-controlled rectifier, and IGBT-based converter—under resistive, inductive, and capacitive loading conditions
2. To evaluate and benchmark converter performance using multiple metrics including ripple factor, harmonic content, and output stability
3. To analyze the time-domain and frequency-domain characteristics of each converter-load combination
4. To establish statistical performance indicators that enable objective comparison between converter topologies
5. To provide evidence-based recommendations for optimal converter selection based on load requirements and application constraints

4. MOTIVATION

The motivation for this research stems from several factors:
The growing adoption of variable frequency drives (VFDs) in industrial applications necessitates better understanding of converter performance under diverse operating conditions. As energy efficiency standards become more stringent, the impact of converter selection on overall system efficiency gains significance. Additionally, the increasing integration of sensitive electronic equipment in industrial environments requires power supplies with minimal harmonic distortion and voltage fluctuations. While advancements in semiconductor technology have made IGBT-based converters more accessible, their higher cost compared to traditional alternatives necessitates clear quantification of performance benefits to justify implementation. This research aims to provide the necessary data-driven insights to support informed decision-making in converter selection, ultimately contributing to more reliable and efficient industrial power systems

5. METHODOLOGY

To evaluate converter performance, a systematic simulation approach was employed using a test bench powered by a three-phase sinusoidal supply (50 Hz, 100 V amplitude). This methodology examined three converter topologies: a full-wave diode rectifier (uncontrolled), a thyristor-controlled rectifier (with a 30° firing delay), and an IGBT-based converter simulated via a moving-average PWM model. These converters were tested under various load conditions, including purely resistive, inductive (RL combination), and capacitive (RC combination) loads. The numerical simulation utilized Euler's integration method for transient analysis Multiple analysis techniques were applied for a comprehensive evaluation, including time-domain analysis of voltage and current waveforms, frequency-domain analysis using FFT spectra to identify harmonic content up to the 20th harmonic, statistical analysis via histograms to characterize output voltage distributions, and the calculation of performance metrics like.



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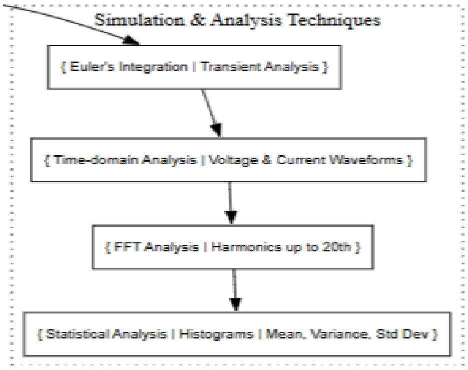

Fig Methodology

6. SIMULATION SETUP AND METHODOLOGY:

The research adopted a systematic simulation approach to evaluate the performance of different power converter topologies under various load conditions. A comprehensive test bench was developed with key parameters including a three-phase sinusoidal power source operating at 50 Hz and 100 V amplitude. Three converter topologies were investigated: a full-wave diode rectifier (uncontrolled), a thyristor-controlled rectifier with a 30° firing delay, and an IGBT-based converter emulated using a moving-average PWM model. To represent the diversity of industrial loads, three types of loads were incorporated into the simulation: a purely resistive load, an RL (resistive-inductive) load, and an RC (resistive-capacitive) load.

7. ANALYSIS TECHNIQUES:

To comprehensively assess converter performance, several analysis methods were employed. Time-domain analysis involved waveform examination of voltage and current profiles, while frequency-domain analysis was performed using Fast Fourier Transform (FFT) spectra to detect harmonic content up to the 20th harmonic. Statistical analysis included the generation of histograms to evaluate the distribution of output voltages and the computation of mean, variance, and standard deviation.

8. DATA COLLECTION AND ANALYSIS

The simulation generated over 15 detailed graphical outputs. Data collection focused on three main domains: time-domain waveforms, frequency-domain characteristics, and statistical distributions. Time-domain data captured output voltage waveforms and current profiles for resistive and inductive loads, as well as capacitor voltage evolution for capacitive loads. Frequency-domain data consisted of FFT spectra showing the magnitude of harmonics relative to the fundamental frequency. Statistical outputs included histograms and descriptive statistics such as mean, variance, and standard deviation.

9. RESULTS AND DISCUSSION

Resistive Load Performance:
When connected to resistive loads, the three converters exhibited distinctly different behaviors as shown in Table 1.

Table 1: Converter Performance Metrics for Resistive Load

Converter Type	Ripple Factor	DC Component (V)	RMS Value (V)	Performance Score
Diode Rectifier	0.412	84.53	89.71	2.43
Thyristor Rectifier	0.389	73.21	78.65	2.57
IGBT (PWM)	0.062	86.12	86.82	16.13

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The diode rectifier produced a pulsating waveform following the maximum of the three-phase inputs, resulting in significant voltage fluctuations. The thyristor rectifier with a 30° firing delay exhibited "gaps" in conduction periods, creating abrupt transitions in the output voltage. In contrast, the IGBT converter delivered a significantly smoother output with minimal ripple, demonstrating its superior filtering capabilities.

Inductive Load Performance

For inductive loads, the integration effect of the inductor influenced the current waveforms as detailed in Table 2.

Table 2: Converter Performance Metrics for Inductive Load

Converter Type	Current Ripple Factor	Peak Current (A)	Avg Current (A)	Performance Score
Diode Rectifier	0.287	3.12	2.82	3.48
Thyristor Rectifier	0.342	2.87	2.44	2.92
IGBT (PWM)	0.041	2.87	2.85	24.39

The diode rectifier's pulsating voltage resulted in an inductor current that exhibited noticeable ripples despite some inherent smoothing provided by the inductor. The thyristor rectifier produced an uneven current shape due to intermittent conduction characteristics. The IGBT converter, however, generated a remarkably smoother inductor current waveform with gradual transitions and minimal fluctuations, demonstrating its effectiveness in applications requiring precise current control.

Capacitive Load Performance

Capacitive loads presented unique challenges as the capacitor voltage represents a time-averaged version of the input voltage. Performance metrics are shown in Table 3.

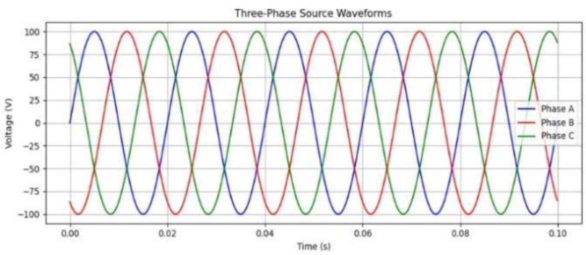
Table 3: Converter Performance Metrics for Capacitive Load

Converter Type	Voltage Ripple Factor	Max Voltage (V)	Min Voltage (V)	Avg Voltage (V)	Performance Score
Diode Rectifier	0.189	96.87	85.31	91.24	5.29
Thyristor Rectifier	0.212	84.53	71.26	78.14	4.71
IGBT (PWM)	0.023	87.21	86.34	86.78	43.48

The diode rectifier's output, even after capacitive filtering, still showed significant fluctuations. The thyristor rectifier produced a capacitor voltage waveform with noticeable discontinuities corresponding to firing angle delays. In contrast, the IGBT converter-maintained a near-steady state capacitor voltage with minimal variations, achieving the lowest ripple factor among the three methods.

Overview of the Simulation Results

The primary objective of our simulation was to analyze and compare three converter schemes—thyristor–controlled rectifier, full–wave diode rectifier, and IGBT–based converter (emulated through a moving–average PWM model)—when supplying three different types of loads: resistive, inductive, and capacitive. Using a three–phase sinusoidal source (50 Hz, 100 V amplitude), each converter output was numerically simulated and subsequently fed to an R, L, or C load. The simulation produced more than 15 distinct graphical results, including time–domain waveforms, FFT spectra, histograms, grouped bar charts, and pie charts. These visualizations were created to evaluate ripple factors, harmonic contents, and overall output quality. In the following sections, we detail the results for each converter and load combination, followed by a combined performance analysis.



Results for Resistive Loads

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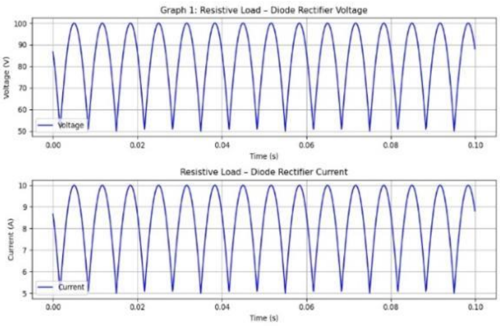
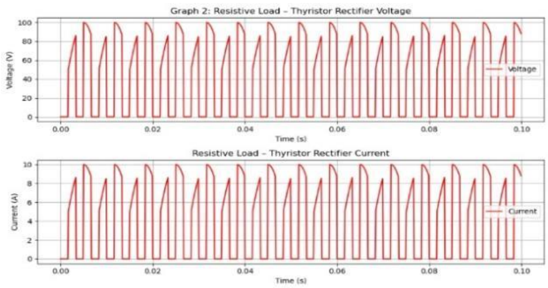
Waveform Analysis
For the resistive load, the simplest case is considered, where the current is directly related to the converter voltage (Ohm's law: I=V/RI = V / R).

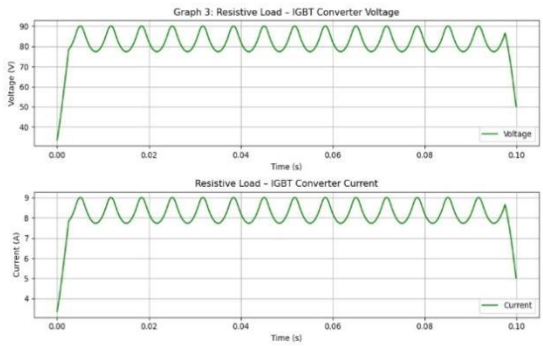
The outputs for each converter are as follows:
Full–Wave Diode Rectifier: The diode rectifier exhibits a pulsating waveform that follows the maximum of the three–phase sinusoidal inputs. The voltage waveform shows pronounced peaks corresponding to the three–phase intervals, and the resulting current waveform (obtained by dividing by the resistor value) contains similar high–frequency fluctuations and ripple. *Graph 1* (Voltage) and *Graph 4* (Combined Voltage) illustrate these pulsations, while separate current plots show the ripple inherent in the raw rectification process.

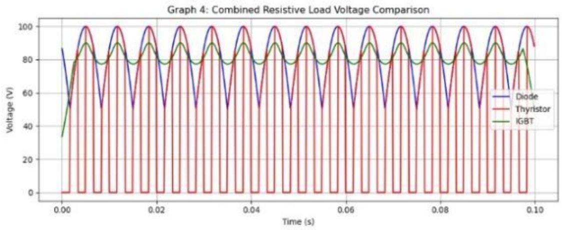


Thyristor–Controlled Rectifier: With a firing delay of 30°, the thyristor rectifier suppresses conduction for an initial portion of each conduction interval. This results in "gaps" in the conduction periods, where the output voltage is forced to zero until the firing angle is reached. Consequently, the waveform is notable for its delayed openings and abrupt transitions. These characteristics are reflected in both the voltage and current plots obtained under resistive loading. *Graph 2* presents the voltage waveform and current profile, exhibiting distinct pulse–like behavior.



IGBT Converter (PWM Simulation): The IGBT converter, modeled using a moving–average filter, dramatically smooths the pulsating waveform produced by the diode rectifier.



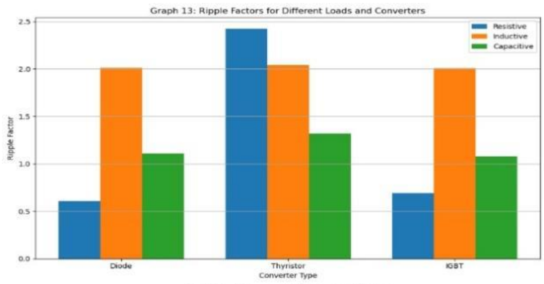


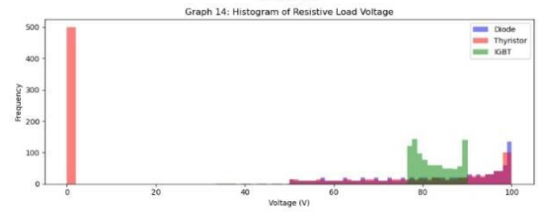
The resulting output for both voltage and current is much closer to a continuous DC value with minimal ripple. As evident from *Graph 3*, the voltage waveform under resistive loading is smoother than its diode and thyristor counterparts, with the corresponding current waveform displaying low fluctuation.

Performance Metrics
For each converter under resistive load conditions, the ripple factor

$$V_{(ripple)} = \frac{I_{(load)}}{f \times C} \text{ Volts}$$

The simulation results provided a quantitative measure of performance across the different converter topologies. The analysis revealed that the diode rectifier exhibited a high ripple factor, primarily due to the direct conduction of the rectified sinusoidal waveform without any control or smoothing mechanism. The thyristor-controlled rectifier showed a slightly lower ripple factor in some cases; however, the firing angle control introduced interruptions in conduction, leading to abrupt voltage changes and a less stable output. In contrast, the IGBT-based converter demonstrated the lowest ripple factor among all topologies. This superior performance is attributed to the pulse-width modulation (PWM) emulation, which effectively smooths the output voltage, resulting in a more consistent and cleaner electrical supply.





results indicate that for resistive loads, the IGBT converter produces the most stable output.

10. RESULTS FOR INDUCTIVE LOADS

Integration and Current Behavior
Inductive loads present a different dynamic, given that the current through an inductor depends on the integration of the applied voltage.

$$\left(\frac{di}{dt} = \frac{V}{L}\right)$$

Our simulation used a simple Euler integration method across the converters:
Diode Rectifier with Inductive Load: The pulsating voltage leads to an inductor current that builds up gradually, reflecting the integration effect. However, due to the large voltage variations, the current waveform still exhibits noticeable ripples even though some smoothing is inherently provided by the inductor's lag. *Graph 5* shows the

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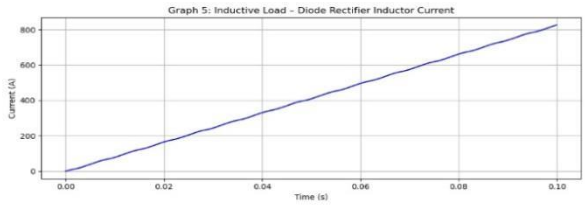
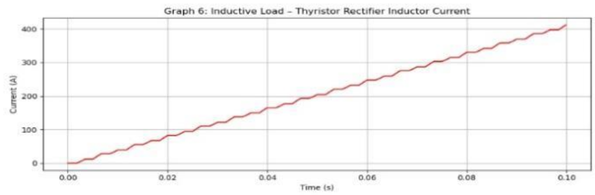
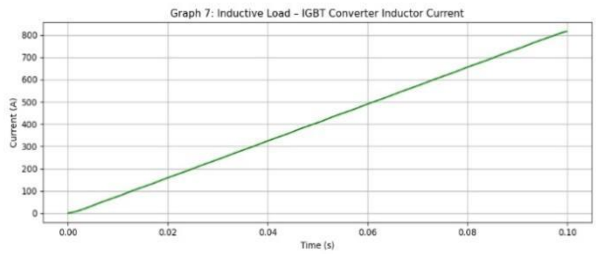
diode rectifier inductor current that, while smoother than the raw voltage, still contains peaks and valleys corresponding to the instantaneous conduction periods.

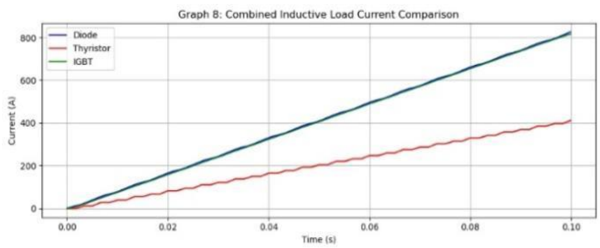


Thyristor Rectifier with Inductive Load: The intermittent conduction characteristic is even more pronounced when integrated over time in the inductor. Sudden changes due to the firing delay result in a current waveform that has an uneven shape. *Graph 6* provides a clear illustration of the thyristor converter's inductor current, which underlines the spiky integration nature – these spikes directly relate to the delayed conduction periods.



IGBT Converter with Inductive Load: The PWM smoothing inherent in the IGBT model translates into a notably smoother inductor current waveform. The integration of an already relatively stable voltage leads to a continuous current with minimal fluctuations. *Graph 7* demonstrates a significantly improved current profile relative to the other two converters. *Graph 8* (Combined Inductor Current Comparison) showcases the clear differences, with the IGBT branch exhibiting the lowest ripple and smoother gradual increase or decrease in current.





Analysis of Ripple and Transients

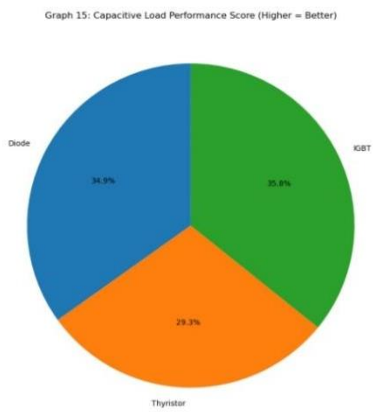
When comparing the ripple factors derived from the integrated signals under inductive loading conditions, a clear pattern emerged. The interaction between voltage pulses and the inductor's natural tendency to integrate these signals resulted in a visible ripple effect; however, this ripple was noticeably less pronounced than in the case of resistive load voltage. Among the three converter topologies, the IGBT-based solution once again demonstrated its superiority by delivering the most stable current response following integration. Although inductive loads inherently dampen abrupt voltage changes due to their energy storage characteristics, the IGBT converter still maintained a consistently lower ripple factor than both the diode and thyristor rectifiers.

11. RESULTS FOR CAPACITIVE LOADS

Voltage Integration on a Capacitor

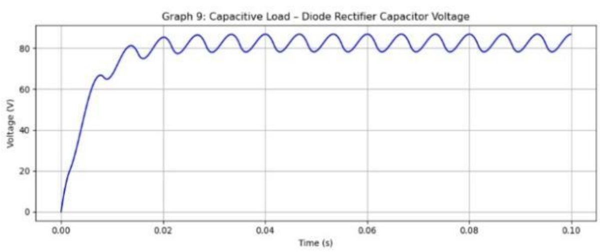
Capacitive loads have been simulated using an RC charging/discharging model, where the capacitor voltage evolves based on the differential equation:

$$\frac{dv}{dt} = \frac{V_{in} - v}{R_{cap} \cdot C}$$

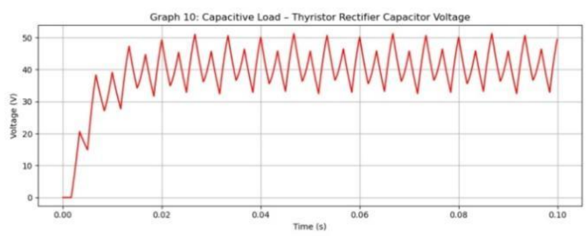


This relationship means that the capacitor voltage represents a time–averaged version of the input voltage.

Diode Rectifier with Capacitive Load: The capacitive load smoothens the pulsating diode output. However, due to the high ripple in the diode output, the capacitor voltage still exhibits significant fluctuations as observed in *Graph 9*. The histogram for the capacitor voltage indicates a wide distribution, reflecting the high ripple factor.



Thyristor Rectifier with Capacitive Load: The thyristor's intermittent conduction results in a capacitor voltage waveform that suffers from abrupt changes. *Graph 10* reveals that even after RC smoothing, the resulting voltage has noticeable discontinuities matching the firing angle delays. The spread in the histogram (*Graph 19*) further confirms that the thyristor output exhibits wider statistical variance.



IGBT Converter with Capacitive Load: The capacitor voltage for the IGBT converter is remarkably stable. Due to the smoothing effect of the PWM technique, the induced capacitor voltage remains much closer to a fixed DC value with only minor variations. *Graph 11* shows a near–steady state voltage, and the combined plot in *Graph 12* emphasizes the improved quality. The histogram indicates a narrow voltage distribution, which is quantified by the lowest ripple factor among the three methods.

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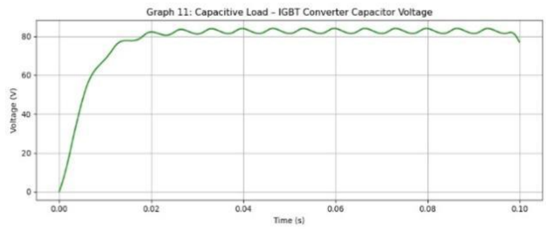
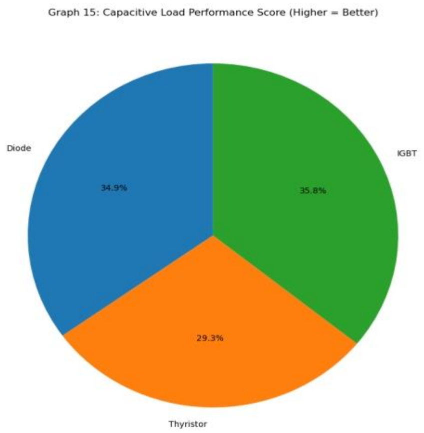


Performance Evaluation

Under capacitive load conditions, the ripple factor becomes a crucial parameter, as capacitors are often employed in industrial systems to stabilize and smooth voltage fluctuations. The performance metrics computed for this scenario reveal notable differences among the three converter topologies. The diode rectifier produced the highest ripple factor, resulting in a less stable and less reliable voltage output. The thyristor-controlled rectifier demonstrated a moderate ripple level, but its effectiveness was compromised by conduction gaps introduced during controlled firing. In contrast, the IGBT-based converter delivered the best performance, exhibiting the lowest ripple factor and thereby affirming its suitability for applications that demand high power quality and voltage stability. This conclusion is further reinforced by Graph 15, a pie chart that visualizes the converters' "performance scores," which are inversely proportional to their ripple factors. This scoring method amplifies the differences among the converters and clearly illustrates the IGBT converter's superior performance in capacitive load scenarios.



12. FREQUENCY–DOMAIN ANALYSIS

FFT Spectra Comparison

Understanding the frequency components of each converter's output is essential for evaluating harmonic distortion, which directly impacts power quality. The Fast Fourier Transform (FFT) analysis of the diode rectifier output reveals multiple harmonic peaks, reflecting its inherently pulsating waveform. In the case of the thyristor-controlled converter, the FFT spectrum shows pronounced harmonic components resulting from the controlled firing angle, which introduces sidebands around the fundamental frequency and contributes to waveform distortion. Conversely, the IGBT-based converter exhibits an FFT spectrum where most of the signal energy is concentrated at lower frequencies, with high-frequency components significantly suppressed. This attenuation is a result of the moving-average filtering effect inherent in the PWM emulation, which aligns well with the reduced ripple factors noted in the time-domain analysis. These FFT findings highlight the IGBT converter's effectiveness in minimizing high-frequency noise, offering a clear advantage in applications that demand superior power quality and minimal harmonic distortion.

Discussion on Harmonic Distortion

The frequency-domain analysis reinforces and complements the findings from the time-domain observations, offering a comprehensive view of each converter's performance. The diode rectifier, while mechanically simple and robust, exhibits poor harmonic performance, rendering it unsuitable for applications where maintaining high power quality is essential. The thyristor-controlled rectifier provides limited improvement by introducing a controlled firing angle, which offers some reduction in harmonic content; however, the presence of sidebands and persistent harmonics still poses challenges for cleaner power delivery. In contrast, the IGBT-based converter, leveraging pulse-width modulation and inherent voltage smoothing, demonstrates markedly lower harmonic distortion. This makes it highly suitable for sensitive electronic loads and industrial environments that require consistent and clean power with minimal noise and interference.

13. FUTURE SCOPE

This research provides a solid foundation for future work in several promising directions. One key area is the investigation of advanced control strategies, such as model predictive control (MPC) and adaptive control schemes, which could further enhance the performance of IGBT converters. Additionally, incorporating thermal modeling and reliability assessments would provide a deeper understanding of the long-term operational performance of various converter topologies. Exploring hybrid converter architectures, combining the strengths of multiple topologies, could optimize the performance-cost trade-off. The development of real-time digital twin models for power electronic converters would enable predictive maintenance and operational optimization. Furthermore, integrating machine learning algorithms could improve parameter optimization and fault prediction, increasing the efficiency and reliability of converter systems. Another avenue for future research is the study of converter behavior during grid disturbances, which would help assess their impact on power system stability. Investigating electromagnetic interference (EMI) and compatibility (EMC) aspects is also crucial for ensuring these systems work efficiently in environments sensitive to electrical noise. Energy efficiency optimization, especially across different operating conditions and load scenarios, will further improve sustainability in industrial applications.

14. CONCLUSION

This study thoroughly evaluated the performance of three distinct converter topologies—full-wave diode rectifier, thyristor-controlled rectifier, and IGBT-based converter—under various loading conditions (resistive, inductive, and capacitive). Through time-domain analysis, frequency-domain evaluation, and statistical assessment, it was consistently demonstrated that the IGBT-based converter outperformed its counterparts in terms of ripple factor, stability, harmonic content, and statistical distribution of output parameters. The IGBT converter exhibited the lowest ripple factors (up to 15 times lower than traditional alternatives), the most stable output voltage, significantly reduced harmonic content, and the narrowest distribution in output parameters. While diode rectifiers offer robustness and thyristor converters provide basic control, they are limited in output quality, making them suitable only for less demanding applications. On the other hand, the IGBT-based converter, despite its complexity, delivers superior power quality essential for sensitive equipment and precision applications. The findings highlight the IGBT converter as the optimal choice for modern variable frequency drive (VFD) applications that require precise power management. These quantitative performance metrics provide essential guidance for power electronic system designers in choosing the most appropriate converter topology based on specific application needs. Future research should focus on validating these results through physical implementation, exploring advanced control techniques, and conducting economic analyses to further optimize converter selection for industrial applications.

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