06-SRJ-480-147

SIAZGA RESEARCH JOURNAL, 2025
Vol. 04 | No. 04 | December - 2025 |250 – 258
DOI: https://doi.org/10.5281/zenodo.18383972

Original Article

Simulation and Experimental Based Analysis of the Power Factor in Phase-Angle-Controlled AC-AC Converter Types

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Abstract

Power electronics is a rapidly evolving field, driven by advancements in converter technology across a wide range of applications. However, the non-linear nature of these converters generates harmonics, adversely affecting their performance and power quality, particularly power factor. This study investigates the supply-side power factor characteristics of different AC voltage converter types that utilize phase-angle control methods. Simulation models for AC voltage converters are implemented in the MATLAB by utilizing Simulink along with the Sim Power Systems toolbox. A comprehensive analysis of power factors is conducted on both simulation models and experimental setups, and the results from simulations and experiments are compared to validate the findings.

Keywords: *AC-AC converters, AC voltage converter, Phase angle control, Power factor, Simulation*

How to cite:
Soomro, Z., Syed, Q. A. S., Soomro, A. H., Shah, A. A., & Latif, A. (2025). Simulation and Experimental Based Analysis of the Power Factor in Phase-Angle-Controlled AC-AC Converter Types. *Siazga Research Journal*, 4(4), 250–258.
https://doi.org/10.5281/zenodo.18383972

INTRODUCTION

Power electronics involves the control and management of power flow. Power electronics is rapidly evolving due to the increasing number of converters employed in various applications (Ashraf et al., 2024). AC-AC converters provide an efficient means of controlling large amounts of energy, allowing for precise control over the output (Prakash et al., 2024). However, each switching event produces discontinuities and harmonic components in the load current, which may adversely influence the accuracy of the firing angle (Sundaramoothy et al., 2024), (Liu et al., 2022). As a result, the presence of harmonics affects both the converter performance and the overall power factor (He et al., 2019), (Heydari et al., 2017).

AC–AC converters are widely employed for controlling AC voltage levels to ensure a regulated and stable AC output (Liu et al., 2022), (Zhang et al., 2014). These converters are generally controlled using TRIACs or thyristor-based switching devices which can be considered as voltage regulator devices that adjust the RMS voltage and power to maintain stability (Nguyen et al., 2012), (Dwivedi et al., 2020). However, AC-AC converters are non-linear systems that generate harmonics, leading to issues such as low power factors, capacitor bank overloading, transformer overheating, metering inaccuracies, and skin effects (Mahar et al., 2011), (Ashraf et al., 2021).

Harmonic currents can also cause significant heating in conductors (Divakar et al., 2009) and are primarily generated by the non-linear characteristics of system devices and loads (Georgakas et al., 2010). Achieving a high power factor is crucial, but determining the most effective control technique can be challenging (Makky et al., 2003), (Ahmed et al., 2003). This study investigates the supply-side power factor

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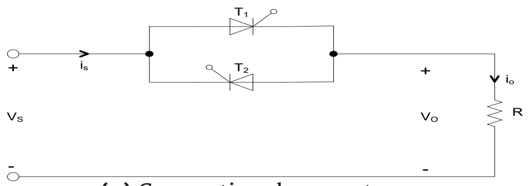
behavior of different AC–AC voltage converters operating under phase angle control methods.

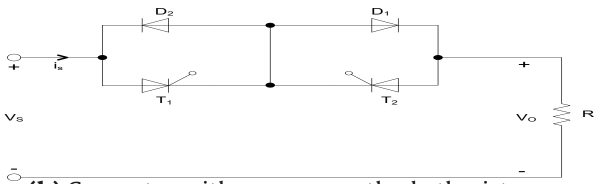
AC voltage converters

AC voltage converters are designed to vary the amplitude of the existing supply voltage. These converters typically have three main types, as illustrated in Fig. 1. These configurations demonstrate the basic structure of an AC voltage converter circuit.

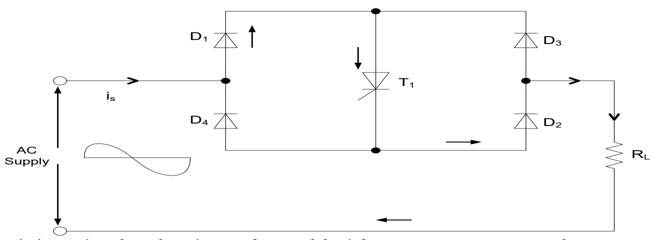
Fig. 1 (a) consists of two SCRs T_1 and T_2 connected in inverse parallel (back-to-back) configuration. Each SCR conducts during one half-cycle of the AC waveform, allowing the circuit to control the voltage applied to load V_o. When the SCRs are triggered (turned on) at a specific phase angle, they conduct and allow current to flow to the load R. By adjusting the phase angle at which the SCRs are triggered, the circuit can regulate the output voltage.



(a) Conventional converter



(b) Converter with common cathode thyristors



(c) A single-thyristor-based bridge converter topology

Fig. 1. Full-wave ac-ac converter types

Fig. 1 (b) has two thyristors connected in a way that their cathodes are tied together. Each thyristor conducts during one half-cycle of the AC waveform, allowing the circuit to control the voltage applied to the load. By triggering the thyristors at specific phase angles, the circuit can regulate the output voltage. The common cathode configuration simplifies the gate drive circuitry, as only one isolated gate drive is required.

A bridge converter using a single thyristor for AC voltage conversion typically employs a diode bridge configuration with one thyristor controlling the flow of current, as shown in Fig. 1 (c). It has a diode bridge (4 diodes) that rectify the AC voltage, and a single thyristor is placed in series with the load, controlling the current flow. By triggering the thyristor at specific phase angles, the circuit can regulate the output voltage.

POWER FACTOR

The power factor of an AC voltage converter is a measure of how effectively the converter uses the input power. AC voltage converters, especially those using phase angle control, often have a power factor less than 1 due to the introduction of harmonics and phase shift between voltage and current. A lower power factor indicates higher reactive power, which can lead to increased line currents, higher energy losses, and reduced system efficiency. Thus, power factor correction techniques, such as, passive and active filters, and advanced control strategies are employed to improve the power factor.

Sinusoidal conditions

Power factor PF in preeminent form of sinusoidal circuits, and is defined as the ratio of real power or active power P to apparent power S, as given in eq. 1,

$$PF = {}^{P}/_{S} \quad (1)$$

While the phase variation of sinusoidal voltage and current is the angle Ø, and the power factor is equal to cos Ø, which is specified by eq. 2,

$$PF = \cos \emptyset \text{--} (2)$$

A near-sinusoidal circuit power factor can be achieved by incorporating a compensator capacitor as an energy-storage link.

Power factor under non-sinusoidal condition

The state of non-sinusoidal circuits comes when a linear circuit is calmed of non-sinusoidal supply voltage, it is prepared of non-linear impedance, although the supply voltage is sinusoidal, or impedance of circuit is comprised power, but not sinusoidal. Hence, the supply-side power factor is determined by the product of the displacement power factor, represented by cos ϕ, and the distortion factor, expressed as the ratio I_F/I_L, as shown in Equation (3).

$$PF = \cos \emptyset_1 \times {}^{I_F}/_{I_L} \text{--} (3)$$

MODELING OF THE FULL-WAVE AC-AC CONVERTERS

MATLAB is used to design, simulate, and analyze the AC converters. Therefore, for modeling circuit models are created using graphical blocks, including power electronics, control systems, and loads. Then the circuit models run to analyze circuit behavior, and to visualize and analyze simulation results.

Simulation modeling of the full-wave AC-AC converters

Simulation of full-wave AC voltage converters involves creating a simulation model to analyze and design the converter's performance. It is performed by SimPowerSystems, a toolbox for modeling and simulating power electronic systems. Basic AC voltage converters of Fig. 1 are modeled in the SimPowerSystems, as shown in Fig. 2, 3 and 4.

3.1.1 AC-AC converter configuration using anti-parallel thyristors

The simulated model of a full wave AC voltage converter which is used for the adaptation of fixed voltage to variable voltage is shown in Fig. 2. It includes V_Supply for the input AC voltage, two thyristor blocks (Thyristor_1 and Thyristor_2) connected in anti-parallel configuration, two pulse generators for generating gate pulses for each thyristor, and measurement blocks for measuring voltage and current.

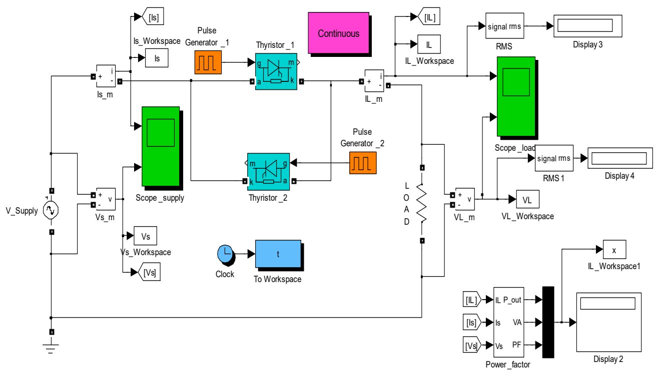


Fig. 2. Simulation model of full-wave ac voltage converter topology using two pairs of thyristor

The simulation model allows analysis of output voltage and current waveforms, effect of firing angle control on output, and power factor and harmonic analysis. Thus, by simulating the model, the converter's performance can easily be evaluated.

AC–AC Converter Employs a Thyristor Arrangement with Common Cathode

The simulated model of a full-wave AC voltage converter with a common cathode of Fig. 1 (b), is shown in Fig. 3, using the MATLAB Sim Power Systems. It includes AC voltage source Vs, two thyristor blocks (TH1 and TH2 with common cathode), pulse generator (for gate pulses of each thyrisor), and measurement blocks (voltage and current).

Like the model Fig. 2, the simulation model of Fig. 3 allows analysis of the output voltage and current waveforms, effect of firing angle control, and power factor and performance evaluation. Thus, this setup enables simulation and analysis of the converter's behavior, helping to optimize control strategies and evaluate performance.

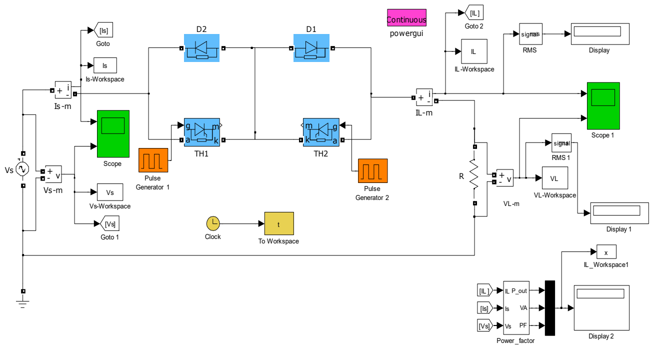


Fig. 3. simulation framework for a full-wave AC–AC converter with a common-cathode thyristor configuration

3.1.3 A single-thyristor-based bridge configuration

The simulated model of a single-thyristor-based bridge configuration of Fig. 1 (c) is as in Fig. 4. It includes AC voltage source, diode bridge (4 diodes), single thyristor block (in series with the load), pulse generator and measurement blocks.

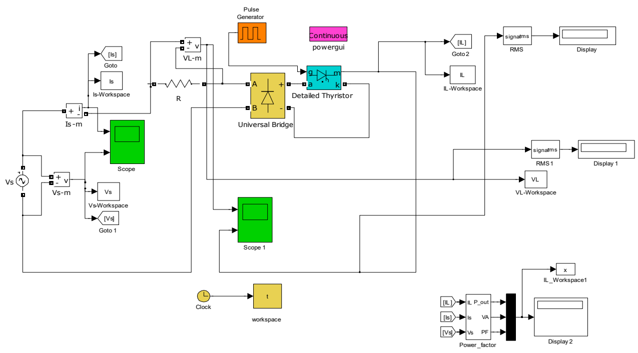


Fig. 4. Simulation modeling of a bridge-type AC voltage converter employing only one thyristor

Experimental Workbench for the Full-wave AC-AC Converters

A choice of power circuits of phase-controlled AC voltage converters is discussed in Section II, Fig. 1. Therefore, useful tools like simulation and power quality analyzer (PQA) are adopted respectively for the simulation and experimental based power factor analysis of talked about converters. Experimental setup also as in Fig. 5.

Power electronic kit has diodes and thyristors to be connected in different configurations of Fig. 1, and a Function generator is connected with the PE kit. Unfortunately, voltmeter and ampere meter of the kit were mal functioning, therefore, multimeter is utilized to determine the current and voltage. Output waveforms are shown in the oscilloscope, and data could easily be extracted from it.

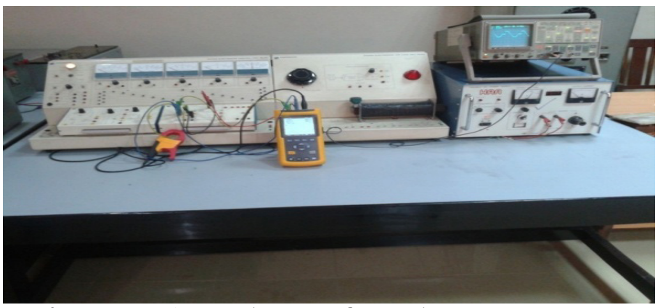


Fig. 5. Experimental setup of AC voltage converter

RESULT VALIDATION

4.1.1 AC voltage converter using anti-parallel thyristors

Using the MATLAB's model of Fig. 2, the output characteristics at 60° firing angle of the conventional full-wave AC voltage topology is depicted in Fig. 6.

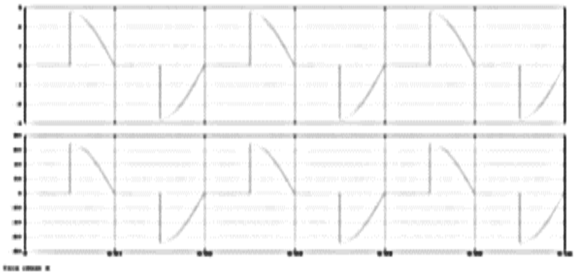
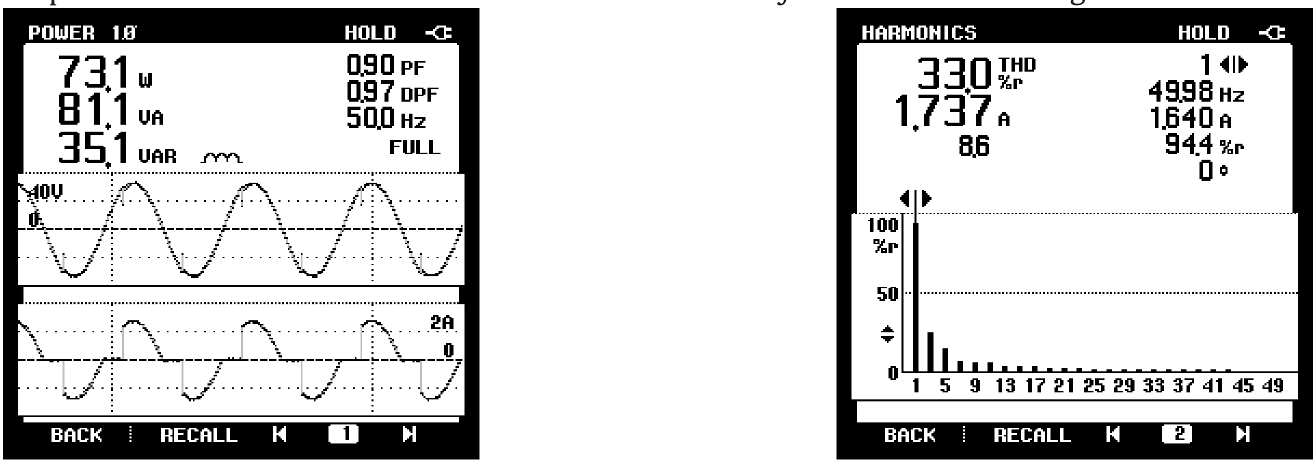


Fig. 6. Power Factor Simulated results at firing angle $\alpha=60^0$

Similarly, using the experimental setup, the output characteristics of the conventional AC-AC converter configuration using anti-parallel thyristors is shown in Fig. 7.



(a) Voltage and current waveform

(b) Harmonic analysis of the current waveform

Fig. 7. Output characteristics using the power quality analyzer

The determined power factor at different firing angles is shown, in Fig. 8. As the firing angle increases, reactive power increases therefore, power factor reduces. Additionally, the experimental results show good agreement with the simulated results.

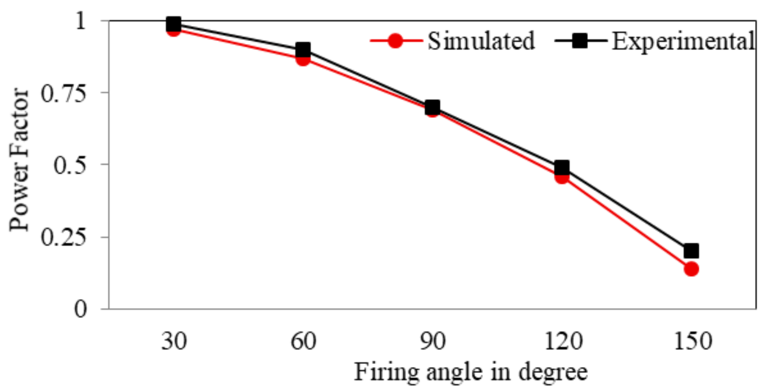


Fig. 8. Experimental and simulated power factor at different firing angles

AC voltage converter with common cathode thyristor

Using MATLAB's model of Fig. 3, the output characteristics at 60° firing angle of the AC–AC converter employs a thyristor arrangement with common cathode is shown in Fig. 9.

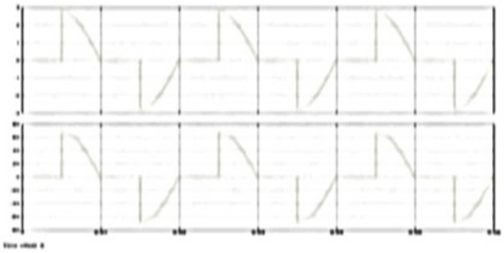
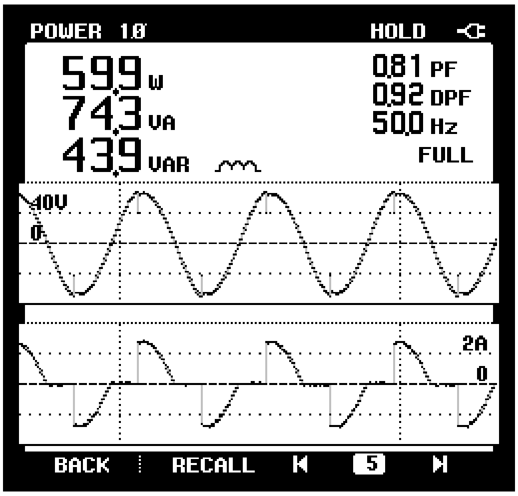
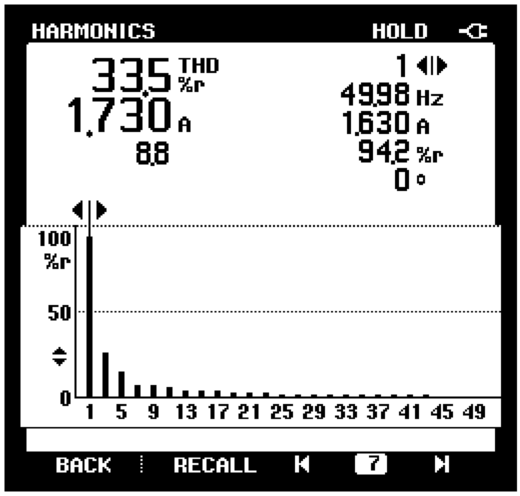


Fig. 9. Power factor simulated at firing angle $\alpha=60^0$

Similarly, using the experimental setup, the output characteristics of the full-wave AC-AC converter with common cathode thyristor, is shown in Fig. 10.



(a) Voltage and current waveform



(b) Harmonic analysis of the current waveform

Fig. 10. Output characteristics using the power quality analyzer

The determined power factor at different firing angles is shown, in Fig. 11. As the firing angle increases, power factors reduce like Fig. 8. Additionally, the simulated results are validated by the experimental results.

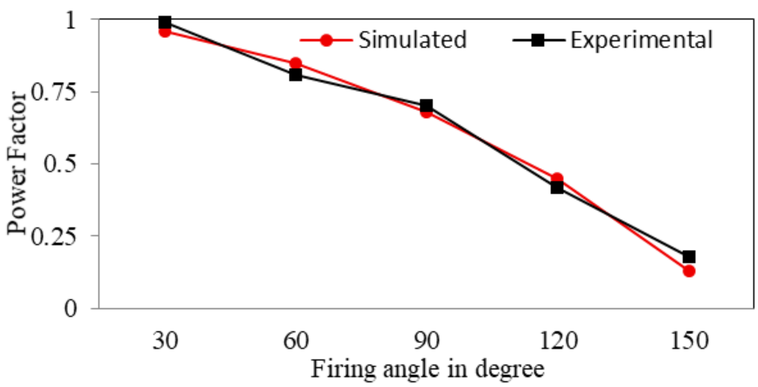


Fig. 11. Experimental and simulated power factor at different firing angles

AC voltage bridge converter with single thyristor

Using MATLAB SimPowerSystems's model of Fig. 4, the output characteristics at 60° firing angle of the a single-thyristor-based bridge configuration is shown in Fig. 12.

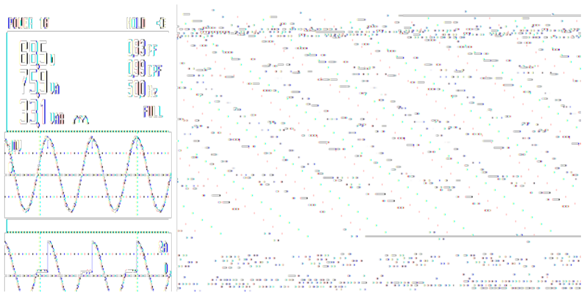
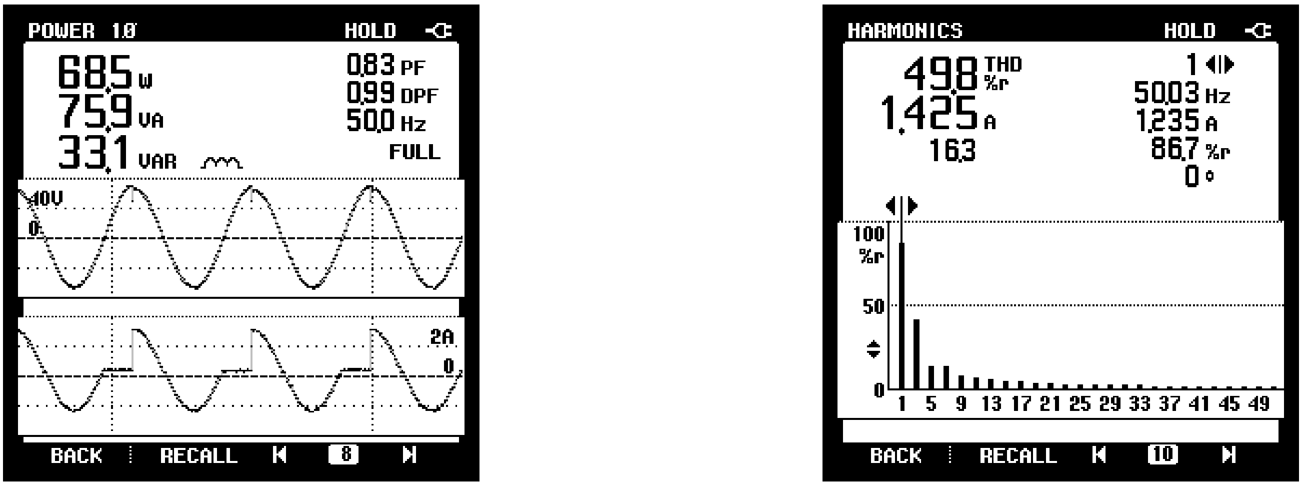


Fig. 12. Power factor simulated at firing angle α=60⁰

Similarly, the performance characteristics of a single-thyristor-based bridge configuration using the experimental setup, are illustrated in Fig. 13.



(a) Voltage and current waveform **(b)** Harmonic analysis of the current waveform

Fig. 13. Output characteristics using the power quality analyzer

The determined power factor at various firing angles is given, in Fig. 14. As the firing angle increases, power factors reduce because active power reduces. The simulation is validated by these experimental results.

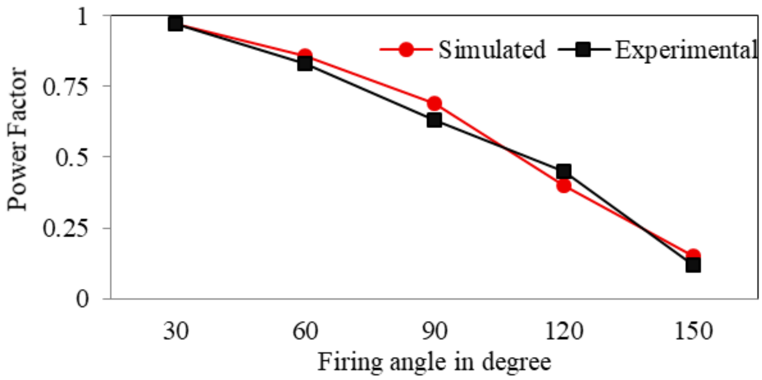


Fig. 14. Experimental and simulated power factor at different firing angles

Power factor of different types of full wave AC-AC converters at different firing angles is shown in Fig. 15. Conventionally used full wave AC voltage converters having two anti-parallel thyrisotrs show better results.

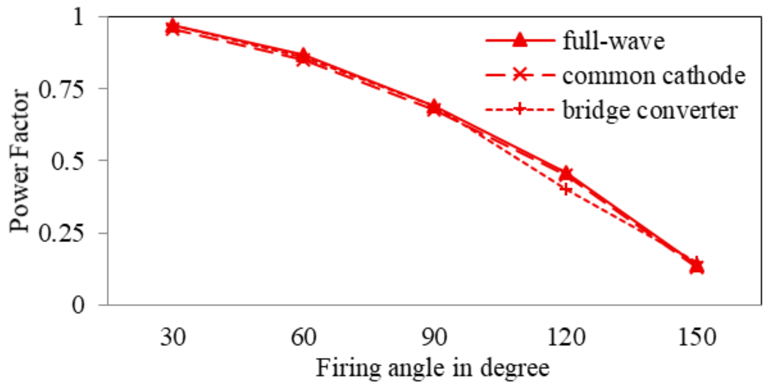


Fig. 15. Comparative analysis of the different AC-AC converters

CONCLUSION

The power factor of a single-phase full wave AC-AC converter types is characteristically analyzed. Key performance parameters, such as, power factor (PF), total harmonic distortion (THD), and power of AC voltage converter types have been analyzed. Comprehensive simulation of AC-AC converters have been developed utilizing MATLAB/Simulink, incorporating SimPowerSystems toolbox for the detailed analysis and evaluation of their performance under various firing angles.

For validation of simulation results, experimental analysis is also presented, and both experimental and simulation results are in good agreement, validating the simulation results. The simulated and experimental results of phase angle-controlled AC voltage converters consistently demonstrate that varying the firing angle significantly affects the supply-side power factor, even when operating with a purely resistive load.

Acknowledgements

Authors acknowledge the support of Prof. Dr. Abdul Sattar Larik of Mehran University of Engineering and Technology for his valuable guidance and supervision.

Competing Interests

The authors did not declare any competing interest.

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