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Performance Analysis of AC Voltage Controller Using Firing Angle and PWM Control for Various Load Conditions

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Abstract — This research focuses on the performance analysis of an AC Voltage Controller (ACVC) utilizing various control techniques—specifically firing angle control and Pulse Width Modulation (PWM) control for different load conditions. The AC Voltage Controller is a power electronic device that regulates AC voltage magnitude without altering its frequency. Simulation models were developed using MATLAB/Simulink for resistive, inductive and single-phase induction motor loads under both firing angle and PWM control techniques. The results highlight that PWM control significantly reduces Total Harmonic Distortion (THD) and improves power factor compared to conventional firing angle control, thereby ensuring enhanced performance and efficiency.

Keywords — AC Voltage Controller, PWM, Firing Angle Control, THD, MATLAB Simulink, Induction Motor.

I. Introduction

An AC Voltage Controller (ACVC) is a thyristor-based device that converts fixed alternating voltage into a variable alternating voltage without changing the supply frequency, whose basic circuit diagram is shown in Fig.1. Such controllers are extensively used in applications like lighting control, heating system and speed control of AC motors. With the advancement of power electronics, phase-controlled converters have replaced traditional devices like autotransformers and magnetic amplifiers. However, ACVCs introduce harmonics, particularly at lower output voltage levels, which affect performance and efficiency. Therefore, analyzing the performance of AC voltage controllers for various load types using both firing angle and PWM control.

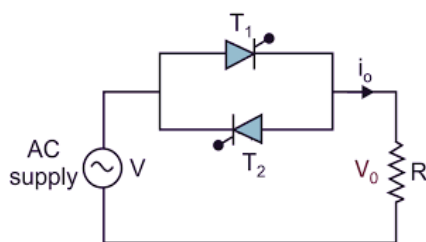


Fig.1: Basic circuit diagram of AC Voltage Controller

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II. PROBLEM IDENTIFICATION AND RESEARCH OBJECTIVES

The major problems in the operation of AC Voltage Controllers with firing angle control are as follows:

- Increased harmonic distortion and poor input power factor.
- High reactive power consumption even for resistive loads.
- Inefficiency of conventional control techniques in reducing THD and improving input performance.

The objectives of this research are:

- To analyze the performance of AC Voltage Controllers with various load types including resistive, inductive, and induction motor loads.
- To implement PWM techniques to reduce harmonics and improve power factor.
- To compare the effectiveness of firing angle control and PWM control using MATLAB/Simulink models.

III. Methodology

The study involves simulation-based analysis using MATLAB/Simulink to model AC Voltage Controllers with both firing angle and PWM control methods. Different load conditions were tested: resistive, inductive and induction motor loads. The procedure included modeling of AC voltage controllers, implementation of control techniques and performance evaluation based on Total Harmonic Distortion (THD), power factor and RMS voltage. PWM control signals were generated by comparing sinusoidal reference signals with high-frequency triangular carrier signals.

A. Operating theories of ACVC with Firing angle control

A.1 ACVC with firing angle control with resistive load

The circuit comprises of two thyristors connected in anti-parallel as shown in Fig.2(a). Anti-parallel connection is done so that thyristor (T_1) is forward biased for the positive half of the input supply voltage and thyristor (T_2) is forward biased for the negative half cycle of the input AC supply.

When T_1 is forward biased, it may be fired to turn it ON. The firing angle of thyristor may be chosen based on the required output voltage. If the output voltage requirement is more, the firing angle (α) should be less. When, T_1 is fired at an angle α , it connects the load to the source for positive half cycle of input. If the load is resistive in nature, the load output voltage follows the envelop of AC supply input. The load current will be in phase with the load voltage as shown in Fig.2(b).

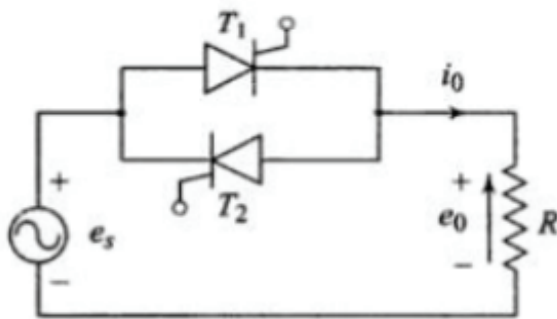


Fig. 2: (a) Single phase ac voltage controller with resistive load.

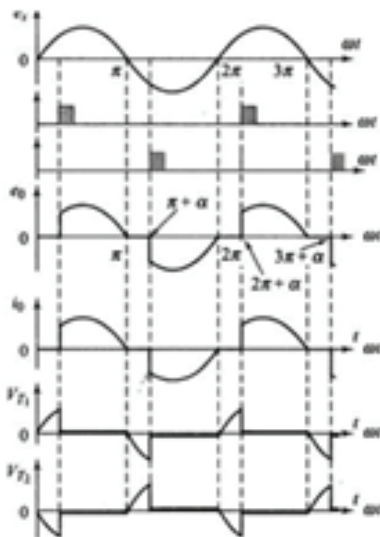


Fig. 2: (b) Voltage and current waveform

At $\omega t = \pi$, the load voltage and current becomes zero. Therefore, T_1 turns off naturally and just after $\omega t = \pi$, T_2 becomes forward biased. At $\omega t = (\pi + \alpha)$, forward biased thyristor T_2 is gated. Hence, it conducts and connected load to the source. The load voltage now follows the negative envelop of the AC input supply and the load current does the same.

Fourier analysis of waveform of output voltage gives:

$$\text{DC Component} = \frac{A_0}{2} = 0 \quad \text{In Polar form}$$

$$A_n = \frac{1}{\pi} \left[\int_{\alpha}^{\pi} V_m \sin \theta \cdot \cos(n\theta) + \int_{\pi+\alpha}^{2\pi} V_m \sin \theta \cdot \cos(n\theta) \right] \quad C_n = \sqrt{A_n^2 + B_n^2}$$

$$B_n = \frac{1}{\pi} \left[\int_{\alpha}^{\pi} V_m \sin \theta \cdot \sin(n\theta) + \int_{\pi+\alpha}^{2\pi} V_m \sin \theta \cdot \sin(n\theta) \right] \quad \phi_n = \tan^{-1} \left(\frac{A_n}{B_n} \right)$$

RMS value of output voltage is:

$$V_{or} = \left[\frac{1}{\pi} \int_{\alpha}^{\pi} V_m^2 \sin^2 \omega t \cdot d(\omega t) \right]^{1/2}$$

$$V_{or}^2 = \frac{V_m^2}{2\pi} \left[\omega t - \frac{\sin 2\omega t}{2} \right]_{\alpha}^{\pi}$$

$$V_{or} = \frac{V_m}{\sqrt{2}} \left[\frac{1}{\pi} \left\{ (\pi - \alpha) + \frac{\sin 2\alpha}{2} \right\} \right]^{1/2}$$

A.2 ACVC with firing angle control with highly inductive load

Fig.3(a) shows the circuit diagram of ACVC with highly inductive load and Fig.3(b) shows the waveforms associated with the circuit. During positive half cycle, T_1 is forward biased and T_2 is Reverse biased. If T_1 is fired at $\omega t = \alpha$ during positive half cycle, load current i_o will build from $\omega t = \alpha$ as shown in Fig.3(b). At $\omega t = \pi$, the input voltage becomes zero but, due to inductive load, current becomes zero lately and T_1 continues to conduct until load current becomes zero at $\omega t = \beta$. During negative half cycle T_2 is fired at $\omega t = \pi + \alpha$ and negative load current builds up from $\omega t = \pi + \alpha$ and so on.

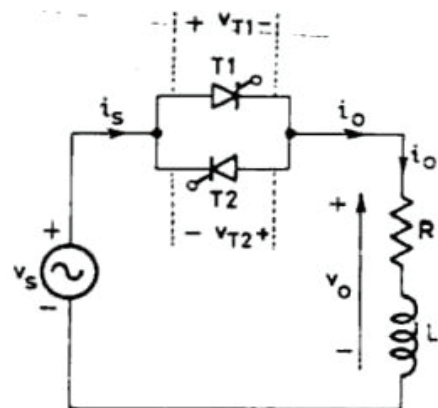


Fig.3(a) Circuit diagram of ACVC with inductive load

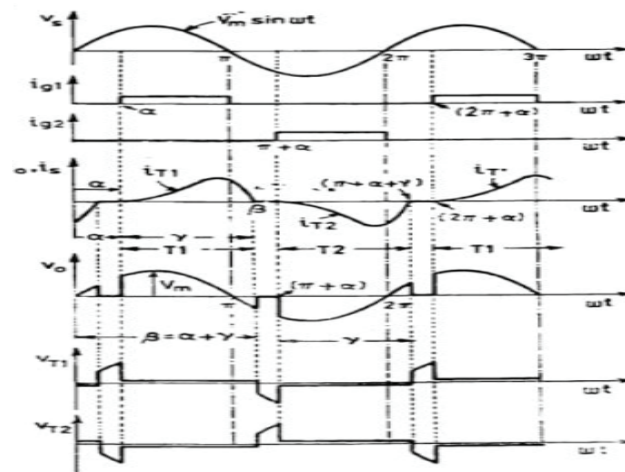


Fig.3(b) waveforms associated with ACVC with inductive load

B. ACVC with PWM control

Circuit diagram of ACVC with PWM control is same as shown in Fig.(a) with Thyristors replaced by GTO switches. The GTO switch (T_1) is turned ON and OFF several times during positive half cycle and GTO switch(T_2) is turned ON and OFF several times during negative half cycle. The switching instants ($\theta_1, \theta_2, \theta_3, \dots$) of switches T_1 and T_2 are decided by comparing high frequency triangular carrier wave with modulating ac square wave whose frequency is same as the frequency of AC input voltage as shown in Fig.4.

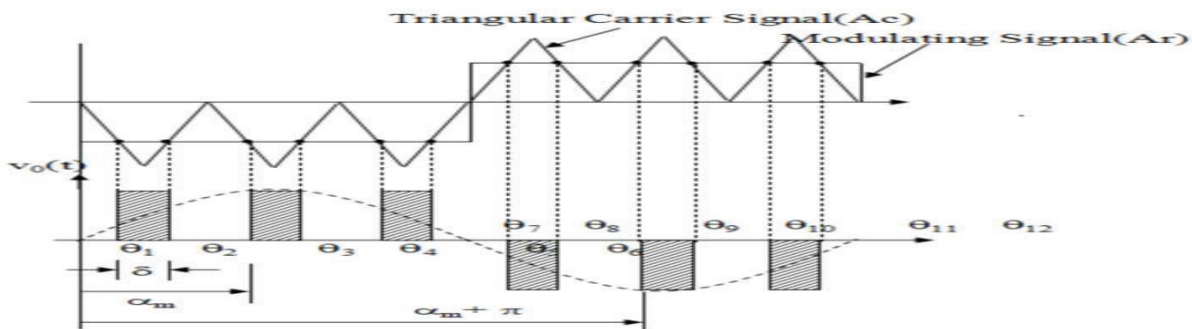


Fig.4: Switching instants generation and waveform of output voltage

The Modulation Index (MI) and Frequency Ratio (FR) for this method are defined as follow:

$$MI = \frac{\text{Peak value of modulating signal } (A_r)}{\text{Peak value of carrier signal } (A_c)} \quad \text{And} \quad FR = \frac{\text{Frequency of triangular carrier signal}}{\text{Frequency of modulating signal}}$$

This method reduces lower order harmonics at the expense of increase in higher order harmonics. The inductance of the load offers high reactance to the higher order harmonics of the output voltage and it acts as filter resulting in nearly sinusoidal load current.

The Total Harmonic Distortion in current is given by:

$$THD = \sqrt{\frac{I_2^2 + I_3^2 + I_4^2 + \dots + I_n^2}{I_1^2}}$$

where:

I_1 = RMS value of the fundamental current

$I_2, I_3, I_4, \dots, I_n$ = RMS values of the 2nd, 3rd, 4th, ... nth harmonic components

IV. Simulation Results

A. ACVC with firing angle control with resistive load

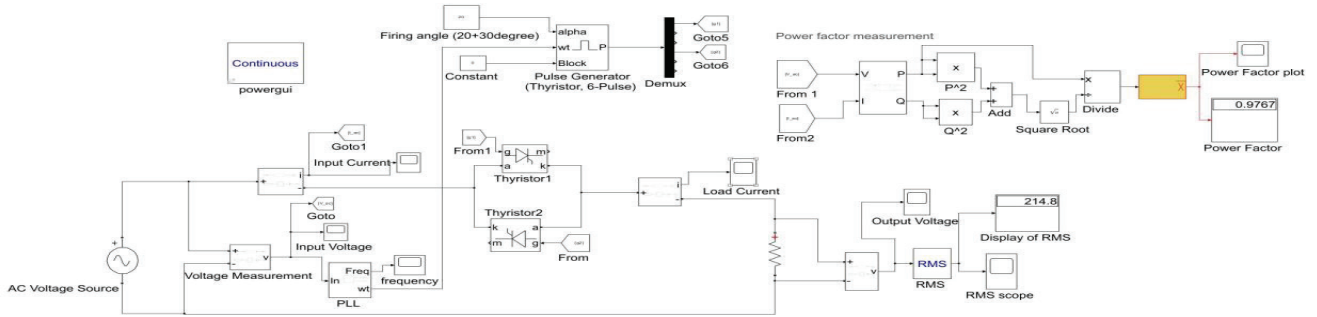


Fig.5: Simulation model of ac voltage controller with firing angle control with resistive load

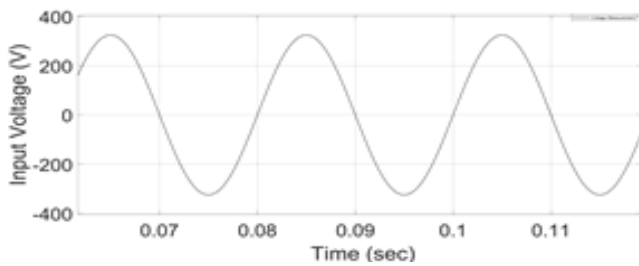


Fig.6: Waveform of input voltage for resistive load

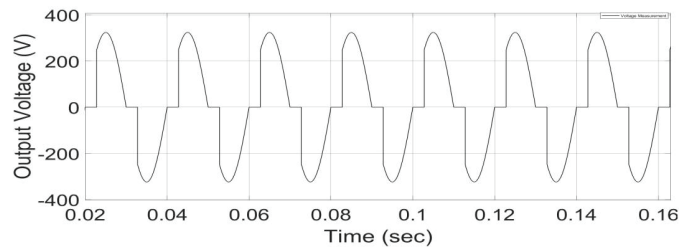


Fig.7: Waveform of output voltage for firing angle = 60° with resistive load

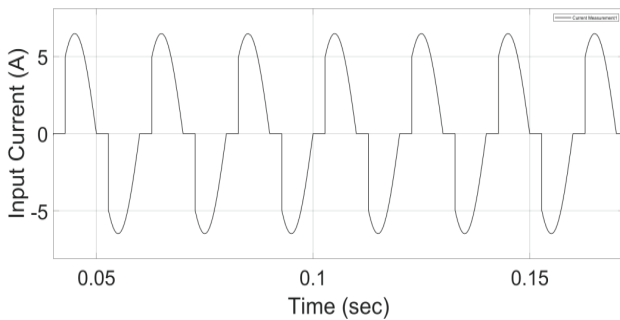


Fig.8: Waveform of input current for firing angle = 60° with resistive load.

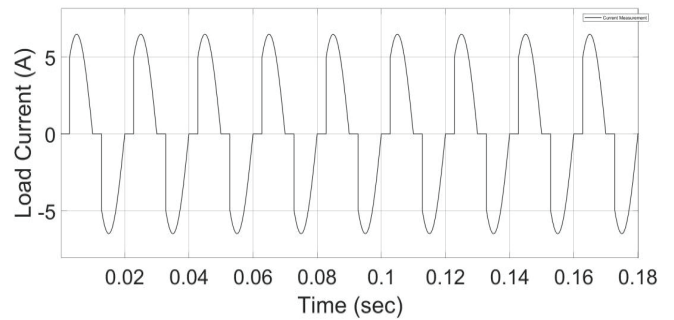


Fig.9: Waveform of load current for firing angle = 60° with resistive load

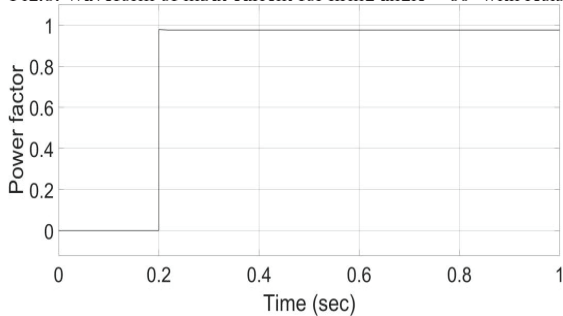


Fig.10: Plot of input current power factor for firing angle = 60° with resistive load.

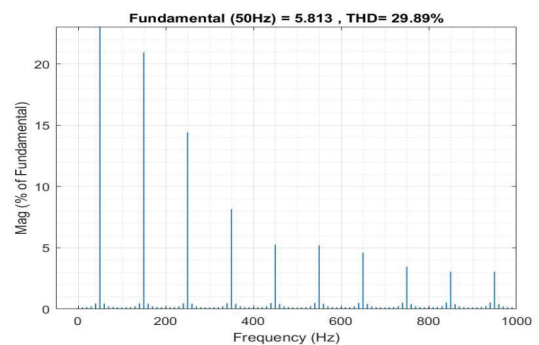


Fig.11: Harmonic components and THD measurement of load current for firing angle = 60° with resistive load

B. ACVC with PWM Control with resistive load

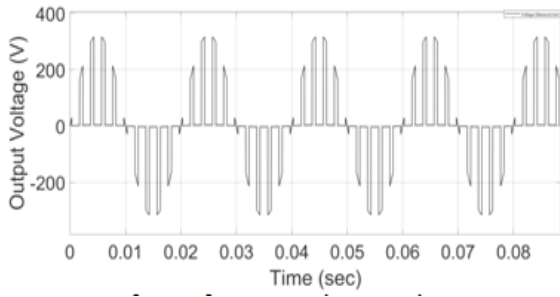


Fig.12: Waveform of output voltage with PWM control for resistive load

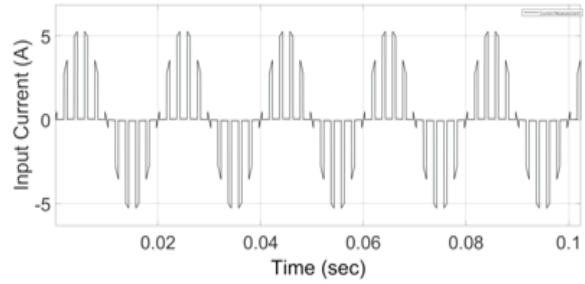


Fig.13: Waveform of input current with PWM control for resistive load

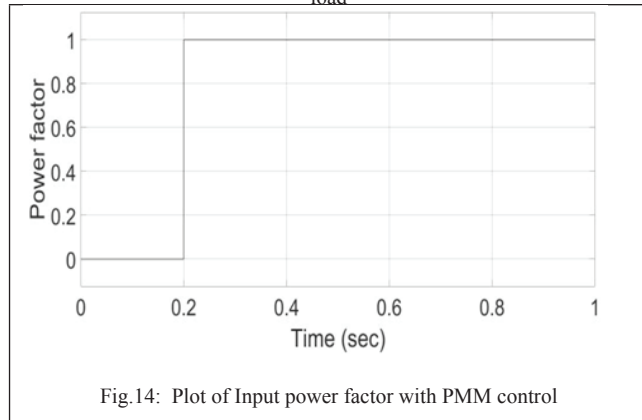


Fig.14: Plot of Input power factor with PMM control

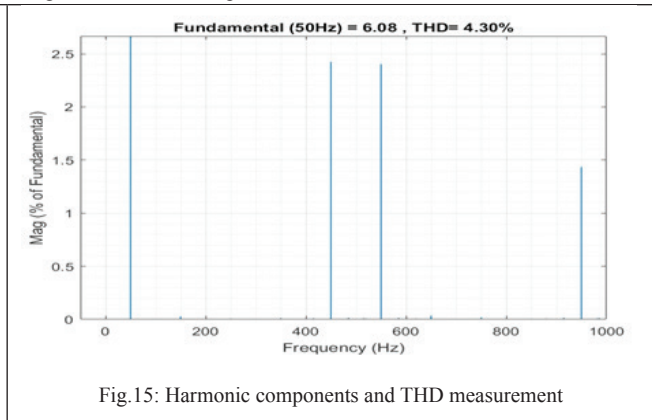


Fig.15: Harmonic components and THD measurement

C. ACVC with firing angle control with highly inductive load

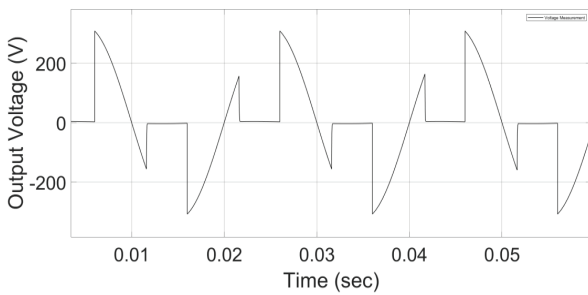


Fig.16: Waveform of output voltage at firing angle = 108° for highly inductive load

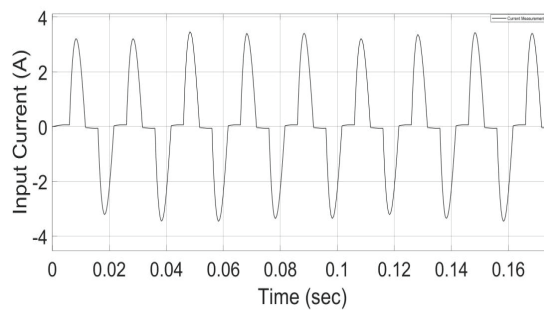


Fig.17: Waveform of input current for highly inductive load

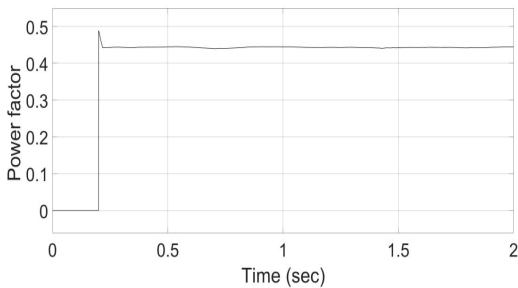


Fig.18: Plot of power factor for highly inductive load

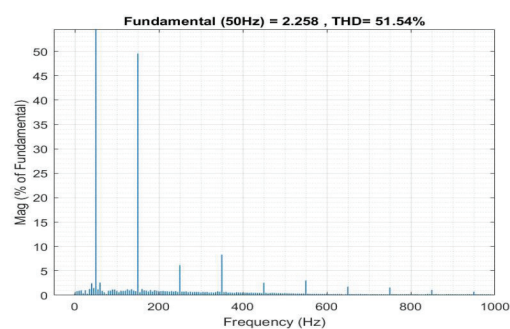


Fig.19: Harmonic components and THD measurement of load current with PWM control

D. ACVC with PWM control with highly inductive load

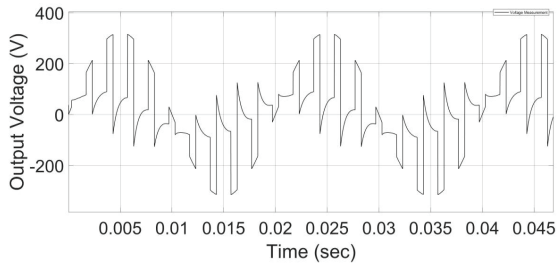


Fig.20: Waveform of output voltage with PWM control for highly inductive load

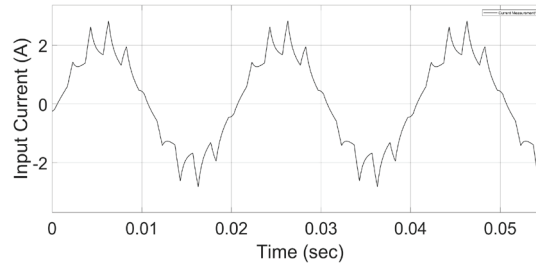


Fig.21: Waveform of input current with PWM control for highly inductive load

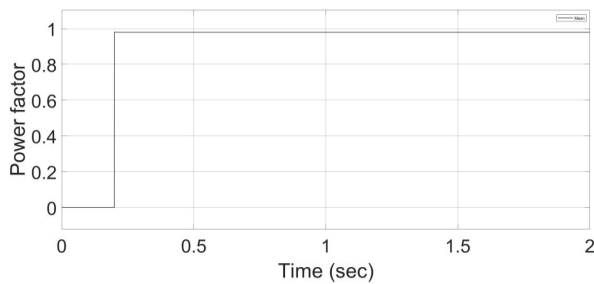


Fig.22: Plot of power factor with PWM control for highly inductive load

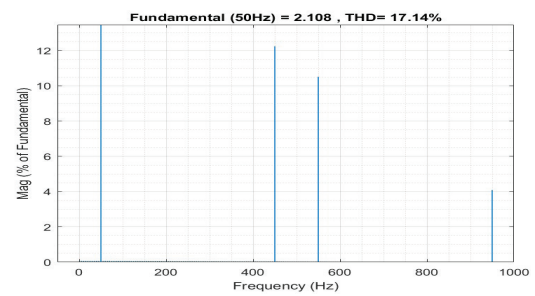


Fig.23: Harmonic components and THD measurement of load current with PWM control for highly inductive load

E. ACVC with firing angle control of single-phase induction motor:

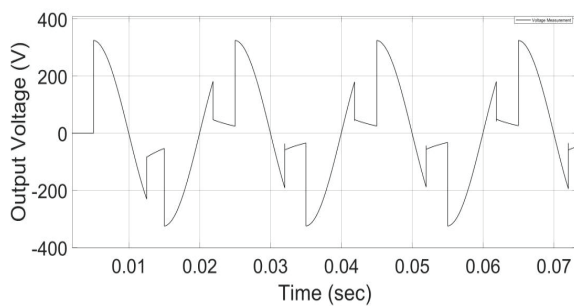


Fig.24: Waveform of output voltage with firing angle control for induction motor load

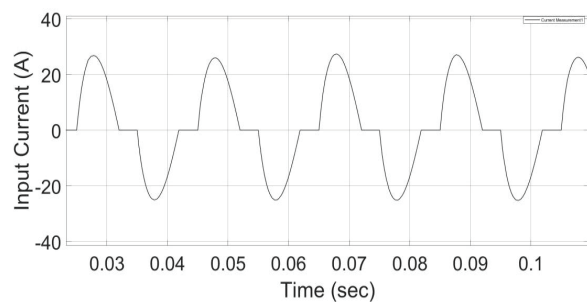


Fig.25: Waveform of input current with firing angle control for highly inductive load

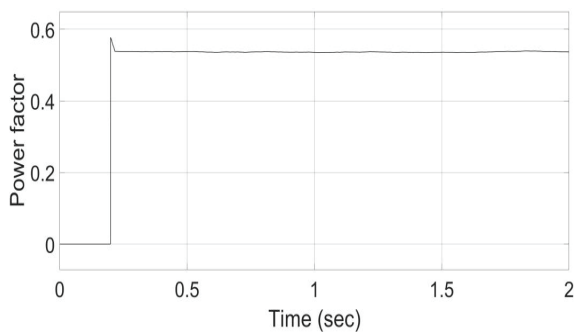


Fig.26: Plot of power factor with firing angle control for highly inductive load

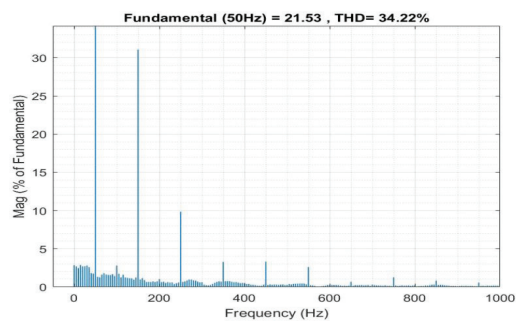


Fig.27: Harmonic components and THD measurement of load current with firing angle control for induction motor load

F. ACVC with PWM control with single phase induction motor load

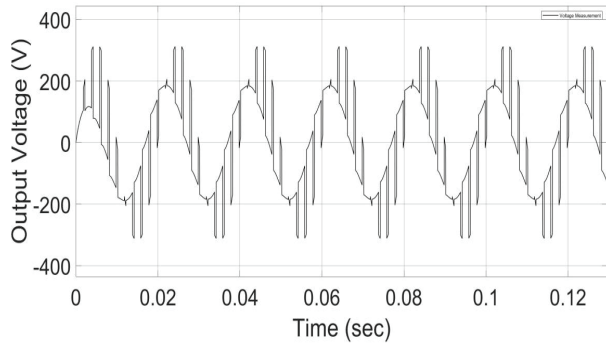


Fig.28: Waveform of output voltage with PWM control for induction motor load

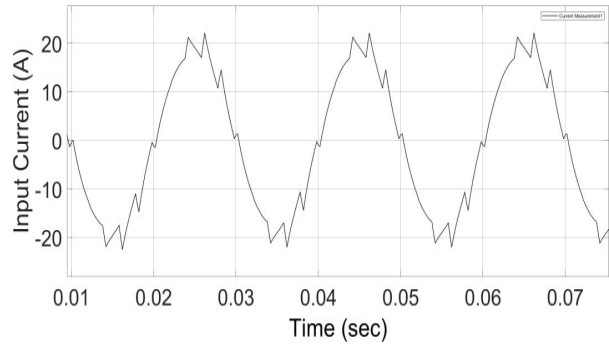


Fig.29: Waveform of input current with PWM control for highly induction motor load

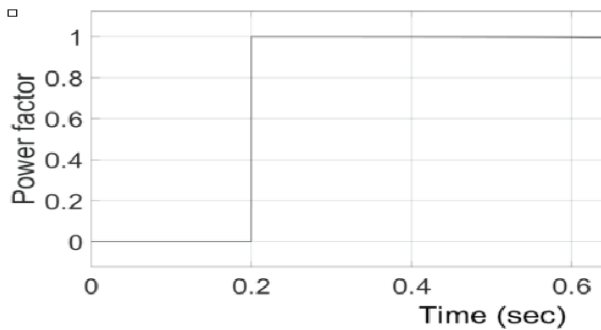


Fig.30: Plot of power factor with PWM control for high induction motor load

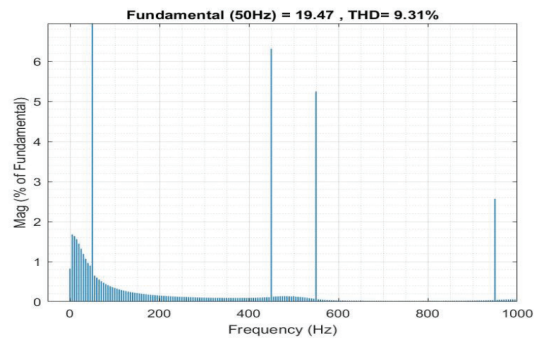


Fig.31: Harmonic components and THD measurement of load current with PWM control for induction motor load

V. Observation and Results

The MATLAB/Simulink models were designed for various configurations, and the results were compared in terms of THD, Power Factor and RMS voltage.

TABLE.1

Summarizes the performance results of each configuration

Configuration	THD (%)	Power Factor	RMS Voltage (V)
ACVC with Firing Angle Control (Resistive Load)	29.89	0.9767	214.8
ACVC with PWM Control (Resistive Load)	4.30	1.000	215.2
ACVC with Firing Angle Control (Inductive Load)	51.54	0.4445	136.0
ACVC with PWM Control (Inductive Load)	17.14	0.9794	134.6
ACVC with Firing Angle Control (Induction Motor)	34.22	0.5364	178.4
ACVC with PWM Control (Induction Motor)	9.31	0.6177	179.0

VI. Discussion and Conclusion

From the simulations, it was observed that firing angle control is simple and effective but introduces significant harmonics at higher delay angles. In contrast, PWM control provides a more sinusoidal waveform, leading to better power factor and reduced THD. For resistive loads, PWM reduced THD from approximately 30% to 4%. Similarly, for highly inductive and motor loads, PWM significantly improved system stability and power quality. These results confirm that PWM control outperforms traditional firing angle control, especially in industrial and dynamic load environments.

Based on the simulation and analysis, it is concluded that the PWM control technique significantly enhances the performance of AC Voltage Controllers compared to conventional firing angle control. PWM provides smoother voltage control, reduced harmonic distortion and improved power factor, making it highly suitable for applications such as motor drives and variable speed control. Future research can focus on implementing advanced control algorithms such as fuzzy logic, neural networks and AI-based optimization for real-time harmonic mitigation.

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