A Study on Control Techniques for Single-Phase Asynchronous Motors: Bipolar and Unipolar Approaches

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Abstract— **This study investigates the performance of bipolar and unipolar control methods for single-phase asynchronous motors. Using MATLAB's SimPower System for modeling and RTLAB for validation, the study highlights significant findings. Unipolar control demonstrated a 20.23% reduction in total harmonic distortion (THD) compared to bipolar control, resulting in improved current waveform quality and enhanced torque response. Bipolar control, while less complex to implement, exhibited higher THD and marginally slower dynamic response. These findings provide actionable insights for optimizing motor control systems in various industrial and domestic applications.**

Keywords— Single-phase asynchronous motors, comparative study, bipolar control, unipolar control RTLAB validation, SimPower System MATLAB.

I. INTRODUCTION

Single-phase asynchronous motors play a crucial role in a variety of applications due to their simplicity, cost-effectiveness, and compatibility with single-phase power supplies. Over the years, numerous pulse-width modulation (PWM) techniques have been developed to optimize their performance, including sinusoidal PWM (SPWM), space vector modulation (SVM), and third-harmonic injection PWM (THIPWM) [1], [2]. Among these, bipolar and unipolar PWM methods remain widely recognized for their simplicity and adaptability.

Bipolar and unipolar control methods have been extensively studied for their ability to regulate motor operations efficiently. Their key advantages include ease of implementation and versatility in handling various operational scenarios. However, their performance characteristics differ significantly, necessitating a detailed comparative analysis to guide their application in real-world systems.

Recent research has explored advanced PWM techniques to improve motor performance. For instance, studies by Chen et al. (2021) highlight the benefits of unipolar control in reducing harmonic distortion and improving power factor. Similarly, Rodriguez et al. (2020) emphasize the potential of space vector modulation for precise motor control. While these studies provide valuable insights, they also underscore the need for comprehensive evaluations of foundational methods like bipolar and unipolar control.

This paper aims to bridge this gap by providing a detailed comparison of bipolar and unipolar PWM strategies for single-phase asynchronous motors. Through MATLAB SimPower System modeling and RTLAB validation [3], this study evaluates their performance in terms of speed response, current waveform quality, and harmonic distortion. By combining simulation and real-time validation, the findings aim to guide engineers and researchers in selecting the most suitable control method for specific applications.

The subsequent sections provide an overview of single-phase asynchronous motors, a detailed examination of bipolar and unipolar control techniques, and a description of the experimental setup. The results from MATLAB simulations and RTLAB validations are then analyzed, followed by a discussion of the implications for real-world applications. The paper concludes by summarizing key findings and suggesting directions for future research.

II. SINGLE-PHASE ASYNCHRONOUS MOTOR

Single-phase asynchronous motors (SPAM), usually referred to as induction motors, are extremely adaptable electrical devices with a variety of applications. It has several benefits that make it a popular option in a variety of circumstances. The simplicity of SPAM is one of its primary benefits. With a static stator and revolving rotor, the motor design is simple. In terms of manufacturing, maintenance, and overall operational efficacy, this simplicity helps save costs [4], [5] The single-phase asynchronous motor is suitable for domestic and small-scale industrial applications where three-phase power may not be easily accessible because it is specifically designed to run with a single-phase power supply. The need for elaborate power infrastructure is removed because

of this compatibility, which also lowers installation costs. The motor has a wide range of uses, including tiny machinery, pumps, fans, and compressors as well as home appliances such as refrigerators, air conditioners, and washing machines. Its adaptability extends to commercial and industrial environments, where it is employed in HVAC equipment, conveyor systems, and several other types of rotating machinery [4].

The single-phase asynchronous motor is a well-liked option because of its broad availability, compatibility with single-phase power supplies, and versatility in various applications. Its standing as a leader in the field of electrical machinery is largely due to its capacity for delivering dependable performance, cost efficiency, and simplicity of use [5].

A. *Single-phase asynchronous motor principle functioning*

A single-phase asynchronous motor operates on the principle of electromagnetic induction. The stator windings, energized by a single-phase alternating current (AC), create a magnetic field that interacts with the rotor. However, single-phase power alone cannot produce a continuous spinning magnetic field. This limitation is resolved using a capacitor, which generates a phase shift between the main and auxiliary windings, as shown in Figure 1. This phase shift creates an additional magnetic field, enabling the rotor to start and maintain motion.

The equivalent circuit of a single-phase induction motor showing the main and auxiliary windings. The auxiliary winding is connected through a capacitor Cs to create a phase shift. Phasor diagram representing the supply voltage V, main winding current I_M, auxiliary winding current I_A, and the resulting total current I. The phase difference ϕ helps generate the starting torque.
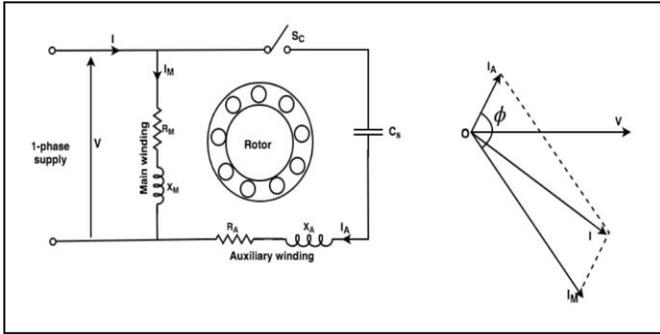

Fig. 1. Single-phase asynchronous motor principle functioning [6]

The capacitor also plays a key role in providing sufficient starting torque. By establishing a phase difference during startup, it allows the rotor to overcome initial inertia and begin spinning efficiently. Additionally, the capacitor improves the motor's power factor, which is typically lower in single-phase motors compared to three-phase systems. A properly designed capacitor enhances overall efficiency and minimizes power losses.

Selecting the correct capacitor value is critical for optimal motor performance. The capacitance must match the motor's specifications and the required load. An incorrect value can cause inefficiencies, overheating, or motor failure. For example, an oversized capacitor may result in unnecessary power consumption, while an undersized one may fail to generate adequate starting torque.

B. *Types of single-phase induction motors*

Single-phase asynchronous motors (SPAM) are categorized based on their starting mechanisms [7], [8]:

- Split-phase motors, capacitor-start motors, capacitor-start capacitor-run (CSCR) motors, permanent-split capacitor (PSC) motors, and shaded-pole motors represent common types.

- Each type differs in its auxiliary components and starting methods, tailored for applications with varying torque and efficiency requirements.

In this study, the **CSCR motor** is used. Its combination of starting and running capacitors provides high starting torque and efficient operation, ideal for demanding applications like pumps and air compressors.

III.   SINGLE PHASE INVERTER

The primary function of a single-phase inverter is to generate a sinusoidal output voltage waveform that mimics utility-supplied AC power. This is achieved by rapidly switching DC voltage across the load using power electronic switches, such as metal-oxide-semiconductor field-effect transistors (MOSFETs) or insulated gate bipolar transistors (IGBTs) [9], [10].

A full-bridge single-phase inverter, illustrated in Figure 2, consists of four power electronic switches configured in a bridge arrangement with two legs [11], [12], [13]. Each leg contains two switches: one connected to the positive DC voltage source and the other to the negative DC voltage source. By controlling the switching sequence of these components, the inverter effectively converts DC power to AC power with high precision [14].
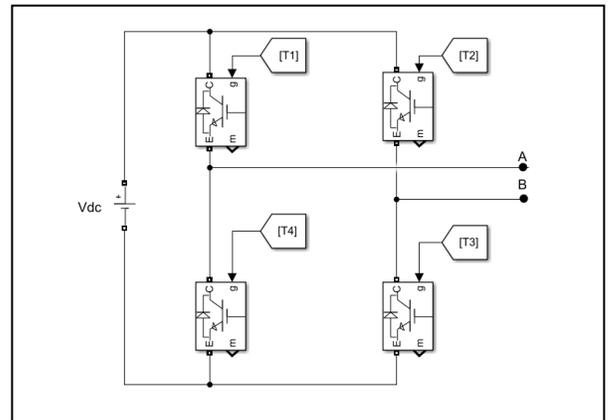

Fig. 2. Single-phase inverter circuit diagram

To prevent short circuits, it is necessary that

$$T_1 \neq T_4 \quad and \quad T_2 \neq T_3 \tag{1}$$

A. Bipolar control of single-phase inverter

In bipolar control, T_1 and T_3 the switches are closed simultaneously during half of the period. The rest of the period involves the closure of the switches T_2 and T_4 When are closed, the two other switches must be open. The output voltage V_{AC} can only take the following two values, All the data is contained in the following table [1], [2], [11], [15]:

TABLE I.   CONDUCTION SEQUENCES

Time	Output current	Output voltage	Controlled switches	Conducting elements
$t_1 < t < \dfrac{T}{2}$	$i_{AC} > 0$	$V_{AC} > 0$	$T_1 . T_3$ ON	T_1 and T_3
$\dfrac{T}{2} < t < t_1$	$i_{AC} > 0$	$V_{AC} < 0$	$T_2 . T_4$ ON	D_2 and D_4
$t_2 < t < T$	$i_{AC} < 0$	$V_{AC} < 0$	$T_2 . T_4$ ON	T_2 and T_4
$0 < t < t_1$	$i_{AC} < 0$	$V_{AC} > 0$	$T_1 . T_3$ ON	D_1 and D_3

B. Unipolar control of single-phase inverter

The bridge control is no longer symmetrical, where is not necessarily closed simultaneously, and the same applies to T_2 and T_4. During the first half-period, T_1 and T_3 are closed simultaneously, followed by the closure of T_3 and T_4 together. During the second half-period, T_4 remains closed with T_2, and then is closed with T_2. As a result, the voltage V_{ac} can now take the following new values. All the data is contained in the following table [1], [2], [11], [15]:

TABLE II.   CONDUCTION SEQUENCES

Time	Output current	Output voltage	Controlled switches	Conducting elements
$t_a < t < t_1$	$i_{AC} > 0$	$V_{AC} > 0$	$T_1 . T_3$ ON	T_1 and T_3
$t_1 < t < \dfrac{T}{2}$	$i_{AC} > 0$	$V_{AC} = 0$	$T_3 . T_4$ ON	T_3 and D_4
$\dfrac{T}{2} < t < t_b$	$i_{AC} > 0$	$V_{AC} < 0$	$T_2 . T_4$ ON	D_2 and D_4
$t_b < t < t_2$	$i_{AC} < 0$	$V_{AC} < 0$	$T_2 . T_4$ ON	T_2 and T_4
$t_2 < t < T$	$i_{AC} < 0$	$V_{AC} = 0$	$T_1 . T_2$ ON	T_2 and D_1
$0 < t < t_a$	$i_{AC} < 0$	$V_{AC} > 0$	$T_1 . T_3$ ON	D_1 and D_3

IV.   SINGLE-PHASE ASYNCHRONOUS MOTORS MODEL

The operation of single-phase asynchronous motors (SPIMs) is commonly modeled using the dq-axis reference frame. This approach simplifies the motor's dynamic analysis by transforming its stator and rotor quantities into a rotating reference frame.

The mathematical stator voltage of the SPIM in the dq-axis is given by the following equations:

$$\begin{cases} V_{qs} = R_s I_{qs} + \dfrac{d\lambda_{qs}}{dt} - \omega_r \lambda_{ds} \quad where \quad \lambda_{qs} = L_s I_{qs} + M I_{qr} \\ V_{ds} = R_s I_{ds} + \dfrac{d\lambda_{qs}}{dt} - \omega_r \lambda_{qs} \quad where \quad \lambda_{ds} = L_s I_{ds} + M I_{dr} \end{cases} \quad (2)$$

Where V_{qs} and V_{ds} Stator voltages in the q- and d-axes

I_{qs} and I_{ds} Stator currents in the q- and d-axes

λ_{qs} and λ_{ds} Stator flux linkages in the q- and d-axes

R_s and ω_r Stator resistance and Rotor angular velocity

And the rotor voltage is expresed by:

$$\begin{cases} 0 = R_r I_{qr} + \dfrac{d\lambda_{qr}}{dt} - (\omega_r - \omega_s) \lambda_{dr} \\ 0 = R_r I_{dr} + \dfrac{d\lambda_{dr}}{dt} - (\omega_r - \omega_s) \lambda_{qr} \end{cases} \quad (3)$$

Mechanical Equation:

$$\begin{cases} J \dfrac{d\omega_r}{dt} + B\omega_r = T_e - T_l \\ T_e = \dfrac{3}{2} PM (I_{qs} I_{dr} - I_{ds} I_{qr}) \end{cases} \quad (4)$$

Simplified Open-Loop Transfer Function: Combining the electrical and mechanical dynamics and solving for speed

$$G(s) = \frac{\omega(s)}{V_{qs}(s)} = \frac{K}{(J_s + B)(L_s s + R_s) + K_t M} \quad (5)$$

V.   PI CONTROLLER FOR MOTOR SPEED REGULATION

Effective motor speed control requires a dynamic strategy capable of adjusting operating parameters in real time. In this study, a proportional-integral (PI) controller is utilized to regulate the speed of the single-phase asynchronous motor [16], [17].

To maintain fairness in the comparative analysis, the same PI controller configuration is applied to both bipolar and unipolar control methods. This ensures an unbiased evaluation of how each control strategy influences motor performance figure 3.
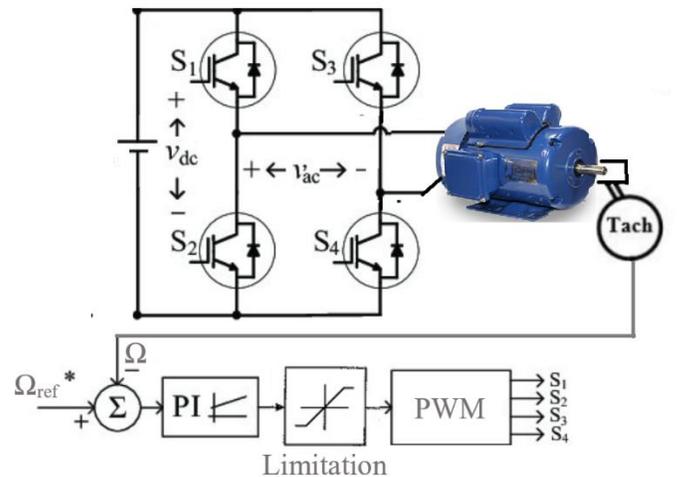

Fig. 3.   PI Controller for single-phase asynchronous motor Speed Regulation

The PI controller's behavior is governed by the following equation[16], [17]:

$$\begin{cases} u(t) = K_p e(t) + K_i \int_0^t e(t)d(t) \\ G_{PI} = K_p + K_i \big/ s \end{cases} \quad (6)$$

Where: $u(t)$ represents the control signal applied to the system, K_p is the proportional gain, influencing the response based on the current error $e(t)$ and K_i is the integral gain, contributing to the control action over time by integrating the $e(t)$

The closed-loop system combines the motor transfer function,

$$T(s) = \frac{G_{PI}(s)G(s)}{1 + G_{PI}(s)G(s)} \quad (7)$$

PI parameters are determined after calculation [3], PI controller parameters are:

$$P = 0.00001 \; and \; I = 0.09 \quad (8)$$

VI. SINGLE-PHASE ASYNCHRONOUS MOTOR CONTROL RTLAB VALIDATION

RTLAB and MATLAB SimPowerSystems were used in conjunction to validate both bipolar and unipolar control approaches for the single-phase asynchronous motor [18]. The motor and the control techniques were modeled and analyzed in depth using MATLAB SimPowerSystems, which was used to simulate first. To assess the performance of the motor under both bipolar and unipolar control, several simulations were run under various operating circumstances and input signals [19].

The results were further validated using RTLAB, a real-time simulation tool, after the MATLAB SimPowerSystems simulations. The two modes of control could be executed in a real-time environment using RTLAB, and the motor's reaction could be evaluated [20].

A. Bipolar control single-phase asynchronous motor RTLAB Validation

In this section Single Phase Asynchronous Machine is used from the specialized power systems toolbox electrical machines, configuration capacitor star run, parameters are nominal power voltage and frequency are $[Pn(VA), Vn(Vrms), f(HZ)] = [.25 * 746 \; 220 \; 50]$, for the resistive torque a pump is used for both methods so:

$$T_{resistive} = \omega^2 \frac{T_r}{\omega_r} \quad (9)$$

Where $T_{resistive}$ is the applied resistive torque on the motor, ω is the motor speed, T_r is the rated torque, and ω_r is the rated speed. And to calculate V_{dc}, V_n is used

$$V_{dc} \geq \sqrt{2}V_n \quad (10)$$

To validate the simulation the system is divided into two subsystems SC and SM the first contains the reference speed as input and the displays like the actual speed of the motor and the current, the display is linked to the OpComm (RTLAB toolbox), for the SM it contains the system the input is linked the OpComm and the OpWriteFile is linked to the output that should be plotted after the rest of the RTLAB.

Figures 3, 4, and 5 represent the responses of speed and current of the bipolar control single-phase asynchronous motor, respectively; Figure 3 shows that the motor speed follows the reference speed with some perturbations; the motor responds quickly to the reference speed and reaches the speed of 1000 rpm in 1s, then even with a change in the reference speed, the speed motor still follows the speed reference speed; to reach 500 rpm it takes 1s and to reach 800 rpm, it takes less then 1s, figure 4 and 5 show that the current is not sinusoidal. And the Total Harmonic Distortion in the current waveform THD=115.53 %.

The Total Harmonic Distortion (THD) was calculated using MATLAB's built-in thd function, which analyzes the output voltage waveform by computing harmonic components based on fast Fourier transform (FFT) analysis. The analysis considered harmonics up to the 25th order relative to the fundamental frequency.
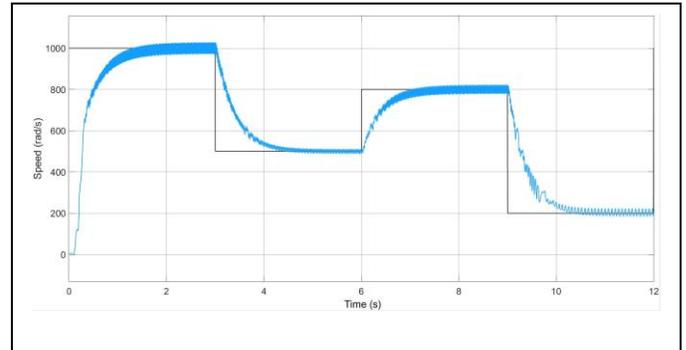

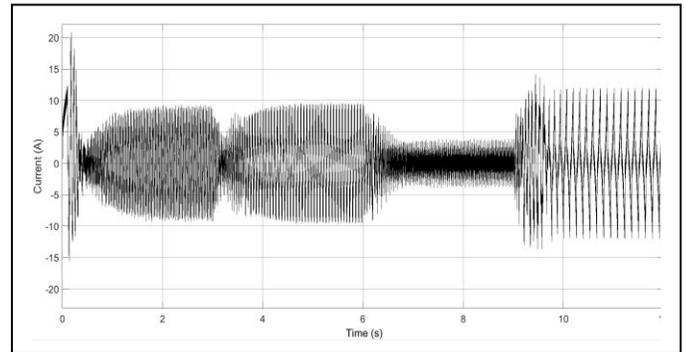Fig. 4. Speed response Bipolar control single-phase asynchronous motor

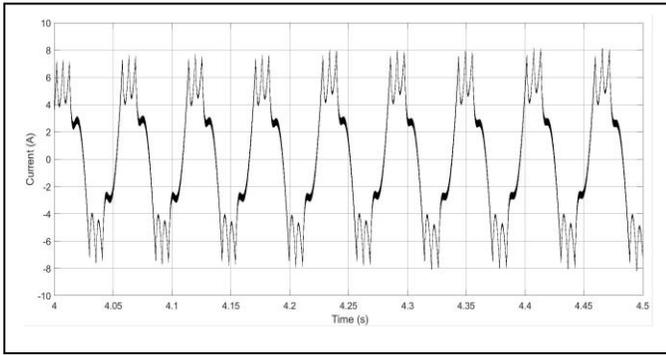Fig. 5. Current response Bipolar control single-phase asynchronous motor

Fig. 6. A close-up view of the current response Bipolar control single-phase asynchronous motor

B. Unipolar control single-phase asynchronous motor RTLAB Validation

In this section, the same system is utilized, with the only difference being a change in the control mode to unipolar control. Figures 6, 7, and 8 represent the responses of Speed and the current of unipolar control single-phase asynchronous motor, In Figure 6, the motor speed tracks the reference speed, resembling bipolar responses with a slightly reduced perturbation level. However, in Figures 7 and 8, the current waveform exhibits greater proximity to a sinusoidal pattern compared to the bipolar control. This observed distinction had a significant impact on the torque response, resulting in reduced losses. Consequently, it is evident that the unipolar control method offers promising advantages in terms of current waveform quality and subsequently enhances the torque response efficiency. The Total Harmonic Distortion (THD) in the current waveform for the unipolar control method is reduced by approximately 20.23 %, indicating a notable improvement in harmonic content
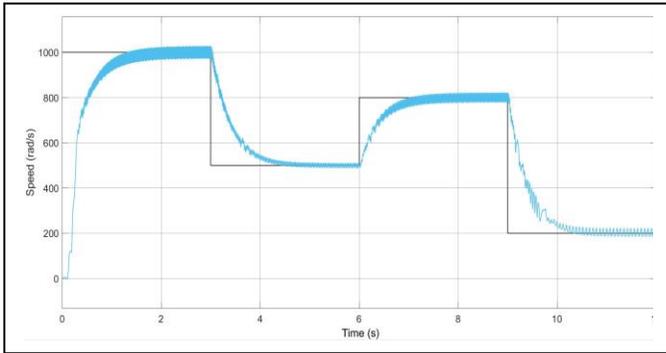

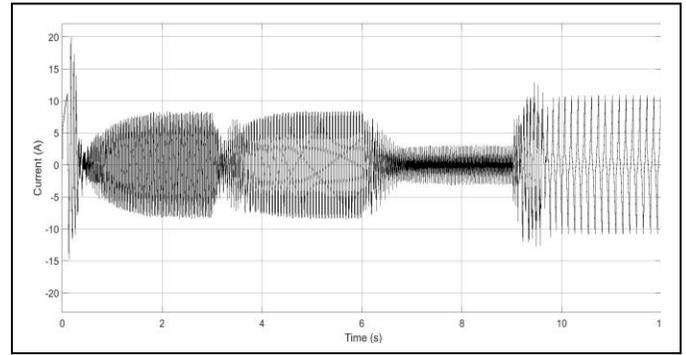Fig. 7. Speed response unipolar control single-phase asynchronous motor

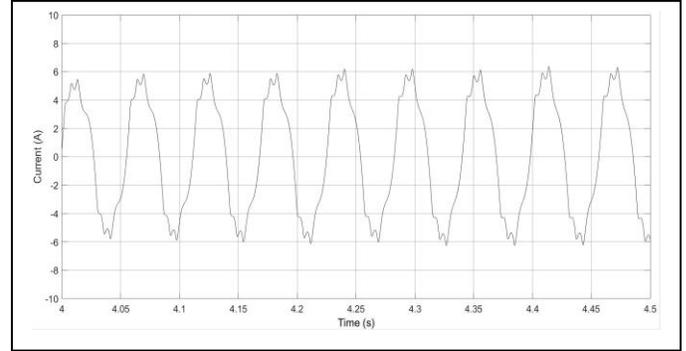Fig. 8. Current response unipolar control single-phase asynchronous motor

Fig. 9. A close-up view of the current response unipolar control single-phase asynchronous motor

VII. CONCLUSION

In conclusion, bipolar and unipolar control strategies for single-phase asynchronous motors were compared. SimPower System MATLAB simulation was used to carry out the analysis, and RTLAB was then used to validate the outcomes. Both bipolar and unipolar control systems have unique benefits and display specific performance traits.

Furthermore, the current waveform of the unipolar control method closely resembled a sinusoidal waveform with reduced harmonics, demonstrating its suitability for applications that require a nearly sinusoidal current. In addition, the speed response of the unipolar control method exhibited fewer disturbances than that of the bipolar control method, demonstrating its greater stability. However, it is noteworthy that the bipolar control technique is considered less complicated and easier to implement than unipolar control, providing practical advantages in terms of simplicity and implementation feasibility.

The benefits of single-phase asynchronous motors must be emphasized. Single-phase asynchronous motors are employed in many applications owing to several advantages.

Single-phase asynchronous motors are cost effective and simple to construct, making them suitable for small-scale and low-power applications. In addition, single-phase asynchronous motors offer a high beginning torque owing to their quick response to the operating speed, which enables them to start and run diverse loads effectively.

The knowledge gathered from this study aids in a better comprehension of the benefits and performance traits linked to each control approach. When choosing the best control method for single-phase asynchronous motor applications, these insights can help engineers and researchers in the field of motor control to make well-informed decisions.

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