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Microcontroller-based speed control of single-phase induction motors: methods, technologies, and implementation developments

Tri Wahono[1], Tole Sutikno[2]
[1]Embedded Systems and Power Electronics Research Group, Yogyakarta, Indonesia
[2]Faculty of Industrial Technology, Universitas Ahmad Dahlan, Yogyakarta, Indonesia

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ABSTRACT

Single-phase induction motors (SPIMs) remain widely used in domestic appliances, ventilation systems, pumps, and small-scale industrial equipment because of their relatively simple construction, reliability, and compatibility with single-phase electrical supplies. However, conventional SPIMs generally operate at nearly constant speeds, creating limitations in applications that require flexible speed regulation, improved energy utilization, and adaptation to varying mechanical loads. This review examines the fundamental methods, power electronic technologies, and control architectures relevant to microcontroller-based speed regulation of SPIMs, with particular attention to research published up to 2015. The discussion covers voltage regulation, TRIAC-based phase-angle control, AC–AC converters, variable-frequency inverter systems, and the integration of microcontrollers with sensing and feedback mechanisms. The literature indicates that voltage-based control offers relatively simple and economical implementation, whereas frequency-based control provides a more direct approach to adjusting motor speed. Nevertheless, motor characteristics, torque requirements, harmonic distortion, and operating conditions must be considered when selecting an appropriate control strategy. The review identifies the need for integrated control architectures that balance implementation cost, speed regulation, energy efficiency, and operational reliability.

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1. INTRODUCTION

Single-phase induction motors (SPIMs) are important components of electrical equipment used in residential, commercial, and small industrial environments. Their popularity is associated with relatively low manufacturing costs, mechanical robustness, and the availability of single-phase electrical supplies. Typical applications include ceiling fans, ventilation systems, water pumps, refrigeration equipment, and household machinery. Despite these advantages, conventional SPIMs are not inherently designed to provide convenient and continuously adjustable speed control.

The main research problem concerns the difficulty of obtaining reliable speed regulation without compromising motor performance and electrical efficiency. Conventional methods frequently employ mechanical regulators or variable AC voltage sources, which may increase system complexity, cost, or maintenance requirements. Electronic control techniques provide opportunities to replace these conventional arrangements with programmable and more flexible solutions. In this context, microcontrollers offer an attractive platform for generating switching signals, processing sensor information, and implementing automatic control strategies.

The development of microcontroller-based motor controllers requires coordination between digital control systems and power electronic circuits. A microcontroller cannot directly supply the electrical power required by an induction motor, but it can generate control signals for switching devices such as TRIACs,

thyristors, and semiconductor switches in inverter circuits. Appropriate isolation and gate-driving arrangements are also necessary to protect low-voltage electronic components from the mains supply. Therefore, understanding the relationship between motor characteristics, power conversion, and embedded control is essential for developing an effective speed regulation system.

This review aims to examine the principal speed control methods, associated electronic technologies, and implementation developments relevant to microcontroller-based SPIM applications. It focuses on research published no later than 2015 to establish a historical and technical foundation for subsequent developments. Particular attention is given to the advantages and limitations of voltage-based and frequency-based approaches. The resulting discussion provides a comparative framework for identifying appropriate control methods and research opportunities.

2. CHARACTERISTICS AND SPEED CONTROL REQUIREMENTS OF SPIMS

The operating characteristics of a single-phase induction motor influence the effectiveness of any proposed speed control technique. Unlike three-phase induction motors, a conventional single-phase stator produces a pulsating magnetic field that can be interpreted as two oppositely rotating magnetic fields. Auxiliary windings and capacitors are commonly employed to establish the starting torque and improve operating characteristics. Consequently, the control strategy must account for the motor configuration, particularly the relationship between its main winding, auxiliary winding, and capacitor arrangement.

The available speed regulation methods can broadly be divided into voltage-based and frequency-based techniques. Voltage-based methods modify the effective stator voltage while maintaining the supply frequency, whereas frequency-based methods change the electrical frequency supplied to the motor. The first approach is generally simpler to implement, especially in applications such as fans with relatively predictable torque characteristics. The second approach provides a more direct means of controlling rotational speed, although it requires a suitable inverter and more sophisticated power conversion circuitry.

An important consideration is that reducing the applied voltage does not necessarily produce an equivalent reduction in motor speed. Induction motor torque capability is strongly influenced by the applied voltage, and excessive voltage reduction can result in insufficient starting or operating torque. Under increased mechanical loading, this condition may cause higher slip, greater current demand, overheating, or unstable operation. Therefore, speed regulation must be evaluated together with motor current, torque capability, temperature, and load characteristics.

3. MICROCONTROLLER-BASED CONTROL ARCHITECTURE

A microcontroller-based speed controller generally consists of a command input, processing unit, synchronization or feedback circuit, power switching stage, and motor load. The command input may be implemented using potentiometers, push buttons, or digital communication interfaces. The microcontroller processes the requested operating condition and generates switching signals according to the selected control algorithm. The power electronic stage then regulates the voltage or frequency delivered to the motor.

Zero-crossing detection is particularly important in microcontroller-based phase-angle control systems. This circuit identifies the instant at which the AC supply waveform crosses zero voltage and provides a synchronization signal to the microcontroller. Following detection, the microcontroller calculates an appropriate delay before triggering the TRIAC through an isolated gate-driving circuit. This arrangement allows the controller to modify the effective RMS voltage supplied to the motor while maintaining synchronization with the AC waveform.

Feedback measurement can improve the accuracy of the overall control system. Speed sensors, optical tachometers, infrared sensors, and current measurement circuits can provide information about the actual motor operating condition. The microcontroller can compare measured values with the desired operating condition and adjust its switching commands accordingly. However, sensor selection must consider measurement accuracy, electrical isolation, response time, cost, and the complexity of signal processing.

4. SPEED CONTROL METHODS AND POWER ELECTRONIC TECHNOLOGIES

4.1. Voltage regulation and TRIAC-based phase-angle control

TRIAC-based phase-angle control is one of the most accessible electronic approaches for regulating the speed of single-phase AC motors. The technique works by delaying the TRIAC firing instant relative to the AC supply zero crossing, thereby changing the portion of each half-cycle delivered to the motor. A microcontroller can perform this timing operation and provide adjustable firing commands based on user

input or feedback information. The relatively small number of switching components makes this technique attractive for low-cost applications.

Salu *et al.* [1] investigated a single-phase AC motor speed regulation arrangement using thyristor-based control. Their study demonstrated the use of electronic switching to provide different operating conditions and regulate motor speed. The findings support the feasibility of semiconductor-based voltage regulation as an alternative to conventional arrangements. Nevertheless, the study also illustrates the importance of coordinating the switching process with the required motor operating conditions.

A related comparison was presented by Purnomo *et al.* [2], who investigated a conventional Variac and an AC–AC converter employing TRIAC phase-angle control with a TCA785 triggering circuit. Their experimental results demonstrated that the electronic converter could provide speed variation comparable to the Variac under both unloaded and loaded conditions. In the loaded condition, the reported speed ranges were relatively close for the two supply arrangements. This finding suggests that electronic voltage regulation can provide a practical and more compact alternative to conventional variable AC voltage sources.

Narayanan *et al.* [3] also examined phase-angle control for single-phase induction motor speed regulation using an AC–AC voltage controller. Their investigation considered the effects of harmonic distortion and total harmonic distortion associated with the switching process. These considerations are important because phase-angle control produces a non-sinusoidal voltage waveform rather than a pure sinusoidal supply. Consequently, the simplicity of TRIAC-based control must be balanced against waveform quality, motor heating, electromagnetic interference, and acoustic noise.

4.2. AC–AC converters and alternative switching techniques

AC–AC converters provide another important implementation approach for controlling the effective voltage supplied to SPIMs. These converters can employ TRIACs, thyristors, or other semiconductor switching devices to regulate the output voltage. Compared with conventional Variac systems, semiconductor converters can offer reduced size, lower mechanical complexity, and easier integration with digital controllers. Their operation can also be coordinated with programmable control algorithms.

Sundareswaran *et al.* [4] evaluated energy-efficient speed control techniques for capacitor-run SPIMs used in domestic fans. Their investigation considered phase-angle control, pulse-width-modulated AC chopper techniques, and integral-cycle control. The study provides a useful comparison of power conversion approaches under application-specific operating conditions. In particular, it demonstrates that the choice of switching method can influence the performance and energy characteristics of capacitor-run motors.

The suitability of an AC–AC converter depends on the intended load and required operating range. Phase-angle control is generally attractive when a relatively simple and inexpensive voltage regulator is sufficient. AC chopper approaches provide alternative switching strategies that can be evaluated in terms of waveform quality and power conversion performance. Integral-cycle control offers another implementation option, although its suitability depends on the load's dynamic response and the potential effects of supply waveform modulation.

4.3. Variable-frequency inverter control

Variable-frequency control provides a more direct approach to changing the rotational speed of an induction motor. This method uses an inverter to generate an AC output with an adjustable frequency rather than relying exclusively on changes in the input voltage. A microcontroller can generate the switching sequence or pulse-width-modulation signals required by the inverter. Appropriate coordination between output voltage and frequency is important to maintain sufficient magnetic flux and torque capability over the operating range.

Adam [5] investigated a single-phase inverter circuit for controlling the speed of a capacitor-start and capacitor-run induction motor through frequency variation. The study reported that motor speed changed proportionally with the stator supply frequency under the investigated operating conditions. It also examined changes in voltage, current, power, and slip as the frequency increased. These findings support the technical feasibility of frequency-based speed regulation for single-phase induction motor applications.

However, implementing a variable-frequency inverter for a single-phase motor requires careful attention to its winding configuration. The auxiliary winding and capacitor arrangement influence the motor's magnetic field and operating characteristics. A conventional three-phase inverter control strategy cannot automatically be transferred to every single-phase motor configuration without appropriate modification. Therefore, the inverter topology and switching strategy must be selected according to the particular motor design and intended operating range [6].

5. COMPARATIVE EVALUATION OF CONTROL TECHNOLOGIES

The reviewed technologies demonstrate that no single control method is optimal for every single-phase induction motor application. Voltage regulation is relatively straightforward and economically attractive, whereas frequency regulation offers a more direct means of adjusting rotational speed. AC–AC converters provide an intermediate solution in terms of hardware complexity and implementation cost. In contrast, inverter-based systems generally require more sophisticated switching arrangements but offer greater flexibility in controlling the motor supply frequency.

The principal advantages and limitations of the reviewed speed control techniques are summarized in Table 1. The comparison considers the main control technologies, their implementation characteristics, and their respective technical limitations. In particular, the table highlights the differences between voltage regulation, TRIAC-based phase-angle control, AC–AC conversion, integral-cycle control, and variable-frequency inverter systems. This comparative overview provides a foundation for evaluating the suitability of each technique for different single-phase induction motor applications.

Table 1. Comparative evaluation of speed control methods for SPIMs

Control method	Main technology	Advantages	Main limitations
Voltage regulation	Variac or AC voltage controller	Simple implementation and low control complexity	Limited speed range and reduced torque at low voltage
Phase-angle control	TRIAC or thyristor	Economical and suitable for microcontroller integration	Harmonics, electrical noise, and waveform distortion
AC–AC conversion	AC chopper and semiconductor switches	Flexible voltage regulation and compact hardware	Switching losses and control complexity
Integral-cycle control	Thyristor or TRIAC switching	Relatively straightforward switching strategy	Potential low-frequency power fluctuations
Variable-frequency control	Single-phase inverter	Direct frequency adjustment and wider speed-control potential	More complex power electronics and motor compatibility requirements

The comparison indicates that application requirements should determine the choice of control technology. For domestic fans and similar loads, voltage-based control may provide an acceptable compromise between cost and performance. For applications requiring a broader operating range and better speed regulation, inverter-based frequency control deserves greater consideration. Regardless of the selected method, practical evaluation should include load response, motor temperature, current consumption, efficiency, harmonic distortion, and speed stability.

6. IMPLEMENTATION DEVELOPMENTS AND RESEARCH CHALLENGES

The integration of microcontrollers into motor control systems represents an important development in the transition from manually operated regulators to programmable electronic controllers. Digital control allows switching parameters to be modified through software instead of requiring extensive changes to the hardware configuration. It also provides opportunities to integrate display units, remote commands, sensor monitoring, and automatic operating modes. These features can improve usability and make the controller adaptable to different application requirements.

Despite these opportunities, several technical challenges remain relevant to microcontroller-based SPIM control. The first challenge concerns the nonlinear relationship between supply voltage, electromagnetic torque, slip, and rotational speed. The second involves maintaining stable operation when mechanical loading changes during motor operation. The third concerns the electrical disturbances associated with semiconductor switching and their potential effects on motor performance and electronic control circuits. These challenges demonstrate why an effective controller should not be evaluated solely by its ability to change the motor speed.

Another important research direction involves the development of closed-loop control architectures. Open-loop systems determine switching commands from predetermined settings without continuously measuring the actual motor response. Closed-loop systems, in contrast, use measured speed or other operating variables to correct deviations from the reference condition. This arrangement can improve speed regulation under changing loads, although its performance depends on sensor accuracy, control algorithm design, and response time. Future investigations should therefore examine the integration of microcontrollers, feedback sensors, and suitable control algorithms within a unified system.

Energy efficiency and power quality also deserve greater attention in future implementations. A controller that successfully reduces motor speed may not necessarily reduce total energy consumption if the motor operates inefficiently at the selected operating point. Similarly, phase-angle switching can introduce

harmonics that influence the electrical supply and motor heating. Research should consequently compare control methods using consistent operating conditions and comprehensive performance indicators. Such evaluations would provide a stronger technical basis for selecting an appropriate control architecture.

7. CONCLUSION

This review has examined the principal methods, technologies, and implementation considerations associated with microcontroller-based speed regulation of SPIMs. The reviewed literature demonstrates that voltage regulation, TRIAC-based phase-angle control, AC–AC conversion, and variable-frequency inverter control provide different approaches to achieving adjustable motor operation. Voltage-based methods offer relatively simple and economical solutions, particularly for applications with predictable load characteristics. Frequency-based control provides a more direct approach to speed adjustment but requires more sophisticated power conversion and careful consideration of motor winding configurations.

The integration of microcontrollers provides flexibility in generating switching signals, processing user commands, and implementing feedback control. However, successful implementation depends on appropriate power electronic interfaces, synchronization circuits, electrical isolation, and measurement techniques. The main research gap identified in the reviewed literature is the need for comprehensive performance comparisons that simultaneously consider speed stability, torque capability, energy efficiency, power quality, and changing mechanical loads. Future research should prioritize closed-loop microcontroller-based architectures and application-specific inverter designs to improve operational reliability and control performance. Ultimately, an effective SPIM speed controller should provide not merely adjustable rotational speed but also safe, efficient, and stable motor operation.

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