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A Review of Speed Control Techniques of Induction Motor

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ABSTRACT

This paper provides a comprehensive review of induction motor speed control techniques, highlighting the evolution and current methodologies employed in the field. It discusses various control strategies, including fuzzy logic and vector control, emphasizing their efficiency and adaptability under different operational conditions. The challenges and limitations faced in controlling induction motor speed are also examined, alongside future recommendations for enhancing control methodologies.

INTRODUCTION

Until a few decades ago, variable speed drives were constrained by several limitations, including suboptimal efficiencies, substantial spatial requirements, reduced operational speeds, and so on. Now, with the integration of innovative technologies and IoT capabilities, these systems can be monitored and adjusted in real-time to further optimize their performance and adaptability to changing operational conditions (Panduman *et al*., 2022). Furthermore, as sectors emphasize sustainability, the incorporation of these technologies supports worldwide initiatives to lessen carbon emissions and foster environmentally friendly practices (Sajid *et al*., 2021). Nevertheless, the emergence of power electronic devices such as Power Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) and Insulated Gate Bipolar Transistors (IGBTs), in conjunction with the introduction of advanced Programmable Logic Controllers (PLCs), has radically transformed the landscape (Hallam, 2023).

Presently, variable speed drive systems are characterized not only by their compact dimensions but also by their remarkable efficiency, exceptional reliability, and their capacity to satisfy the rigorous demands of various contemporary industrial sectors (Shakweh, 2018). Induction motors are extensively utilized across diverse applications, encompassing residential, industrial, commercial, and utility sectors. Single-phase induction motors are frequently employed in both domestic and industrial apparatus (Solomon, 2021). The principal advantage of these motors is their capability to operate on a single-phase power supply (Zhang and Zhang, 2020). It is extensively employed in industrial machinery as a substitute for direct current machines due to its capability to attain a rapid torque response (Cai *et al*., 2021). This adaptability allows for enhanced efficiency and reliability in various applications, making these motors a preferred choice in many sectors. Torque response exhibits a high degree of sensitivity to magnetic flux and can be readily altered through variations in operational parameters. The identification of precise parameters is critically significant in achieving the intended performance outcomes (Petit *et al.,* 2019).

Speed Control

The diverse methodologies for the regulation of induction motor velocity encompass pole variation, stator voltage modulation, supply frequency regulation, rotor resistance manipulation, scalar control mechanisms, and vector control techniques (Htun and Aung, 2019). The synchronous velocity of an electric motor is contingent upon two principal parameters. The first parameter pertains to the magnetic poles of the stator, while the second is associated with the frequency of the power supply. The synchronous velocity is articulated in Equation 1 (Takahashi *et al*., 2020).

$$N_s = \frac{120f}{p} \tag{1}$$

where, f = Frequency in Hz, p= Number of poles

The angular velocity of the rotor and the velocity of the rotating magnetic field in an induction motor represent two distinct phenomena (Masala *et al*., 2022). The rotor synchronous speed exceeds the rotor actual speed, with the percentage difference termed as motor slip (Credo *et al*., 2019).

$$s = \frac{N_S - N_r}{N_r} \tag{2}$$

where, Ns = Synchronous speed, Nr = Rotor speed (Gallardo *et al.,* 2022).

$$N_s = k\,\frac{f}{p} \tag{3}$$

Where k is a constant, as shown in equation 3, the synchronous speed of an induction motor is directly proportional to the supply frequency and inversely proportional to the number of stator poles (Rahman, 2016). Therefore, the most effective approach for controlling induction motor speed requires modification of the supply frequency, owing to the predetermined number of stator poles established by design (Wang *et al.,* 2015).

Review of Control Platforms

Induction motors are essential in industry, prompting the development of various control methods to improve performance (Fahassa *et al.,* 2022). Scalar control, vector control, direct torque control, sliding mode control, and adaptive controls present distinct benefits and difficulties that can significantly impact the performance and efficiency of electric motor systems (Ivanov *et al*., 2016). These methods are often selected based on the specific application requirements, such as speed response, torque ripple, and overall system complexity. These methods allow for precise manipulation of motor characteristics, enabling improved efficiency, responsiveness, and overall operational effectiveness in diverse settings (Guo *et al*., 2018; Mertens *et al*., 2019).

Scalar Control is the simplest method, regulating speed by adjusting voltage and frequency. However, it exhibits insufficient precision in torque regulation and dynamic response, rendering it inappropriate for high-performance applications (Ötkun *et al*., 2022; Srivastav, 2023). Vector control, or Field-Oriented Control (FOC), enables separate management of torque and flux, enhancing dynamic performance and efficiency (Jauhar *et al.,* 2022). It is widely used in industrial settings due to its ability to provide smooth torque and speed tracking (Sohail and Ha, 2023; Rosaiah and Kalagotla, 2023). Direct Torque Control (DTC) offers rapid torque response and is effective in handling large speed changes. However, it can suffer from torque variation, which may affect performance under certain conditions (Hazzaz*et et al*., 2021; Sohail and Ha, 2023). Sliding mode control exhibits resilience to parameter fluctuations and external perturbations, making it suitable for systems with high uncertainty (Ghabi, 2018). It ensures stability and performance but can introduce chattering effects (Srivastav, 2023). Adaptive control adjusts parameters in real-time to maintain performance despite changes in system dynamics (Qi *et al*., 2019). This method is beneficial in applications where load conditions vary significantly (Ayesha and Memon, 2022). While these control methods enhance induction motor performance, their effectiveness can vary based on application requirements and operational conditions (Fahassa *et al*., 2022).

In comparison to vector or field-oriented controls, the implementation of the scalar-controlled drive is notably less complex, albeit with reduced performance outcomes (Swami and Jain, 2021). This control method provides limited speed accuracy, especially in the low-speed range and poor dynamic torque response (Swami and Jain, 2021). However, it remains a cost-effective solution for simpler applications where precision is not critical. In such cases, the trade-off between cost and performance often dictates the choice of control strategy, making scalar control a viable option for many industrial settings (Vazan and Cervenanska, 2018). Many researchers have explored fuzzy logic in the context of online efficiency management for induction motor drives controlled indirectly (Zidani *et al.,* 2019).

Advancement in the control techniques for induction motor (IM) drives in electric vehicles (EVs) was demonstrated by implementing a fuzzy controller through a dynamic backpropagation algorithm using an Adaptive Neuro-Fuzzy Inference System (ANFIS) (Joshi and Pius, 2020). The work emphasizes the efficiency and adaptability of fuzzy logic in managing motor control, particularly under varying operational conditions. The simulated results from ANFIS controllers demonstrate superior performance compared to traditional controllers, validating their effectiveness in real-world scenarios (Hasan *et al*., 2023). The implementation of these techniques on DSP hardware further confirms their practical applicability and reliability in EV systems (Huang *et al*., 2023). However, challenges remain in optimizing these systems for diverse driving conditions and ensuring their scalability in commercial applications (Becker *et al*., 2020; Christmann *et al*., 2023)

Abderazak and Farid (2016) introduced the Fuzzy-SMC-PI approach for regulating the flux and velocity of an induction motor. The Fuzzy-SMC-PI integrates Sliding Mode Control and PI control via fuzzy logic; however, it suffers from chattering during switching (Qi *et al.* 2021). Ostermeyer *et al.* (2020) employed a fuzzy logic controller to modify the boundary layer width based on speed error. A fuzzy sliding mode controller (FSMC) for the regulation of induction motor positioning was developed, with notable advantages. The significant drawback of this control is its reliance on equivalent control and system parameters. This dependency can lead to performance issues under varying operational conditions (Bennassar *et al*., 2022).

Li *et al*. (2023) presented a methodology for the identification of time series models, wherein a substantial array of systems characterized by significant variations in parameters across different operational states can be effectively recognized through the application of Fuzzy Neural Networks (FNN). The proposed approach addresses the limitations of conventional linear system identification techniques, which function optimally only within specific conditions, by offering a comprehensive dynamic characterization that facilitates subsequent system control (Mauroy and Goncalves, 2016), the research yielded contributions and addressed numerous issues; however, limitations exist regarding response settling time and rule base selection (Naus and Jeuring, 2017). Notwithstanding these constraints, persistent scholarly inquiry remains committed to the enhancement of these methodologies, indicating that progress in algorithmic development, particularly those employing unscented Kalman filters, has the potential to significantly augment both the efficacy and applicability of TS fuzzy models (Rodriguez and Baruch, 2017; Vafam and *et al.,* 2018).

Zuhair *et al*. (2021); Wu *et al*. (2022) developed a neural network-based computational speed controller that predicts speed and produces a reference voltage to adjust the armature terminal voltage. During the progression of this work, a tri-layer neural network framework was employed to improve motor velocity modulation, and the resulting model exhibited enhanced efficacy in comparison to traditional control paradigms. Neural networks can learn and adapt to the nonlinear characteristics of motors, enhancing control accuracy under varying conditions (You et al., 2021). Although Mahmood's discoveries exhibit considerable promise, it is crucial to take into account the potential obstacles associated with the deployment of neural networks, including the requirement for substantial training datasets and computational capabilities, which may constrain their relevance in certain contexts (Openja *et al*., 2022; Karner *et al*., 2022).

Cai *et. al.* (2020) presented findings on innovations in electric motors and powertrains for new energy vehicles. The permanent magnet synchronous motor exhibits superior performance compared to direct current, induction, and synchronous motors (Kumar and Murmu, 2020**),** Silicon Carbide Metal-Oxide-Semiconductor Field-Effect Transistor (SiC-MOSFET) converters exhibit superior efficiency and driving range compared to Si-based IGBT converters (Loncarski *et al*., 2020). Vaibhavi and Shushil (2018) introduce a Direct Torque Control (DTC) methodology for three-phase induction motors that employs a Fuzzy Logic Controller (FLC) as a viable substitute for the conventional Proportional-Integral (PI) controller (Pandey, 2020). In this work, the approach for regulating real-time flux and torque values through optimal inverter switching based on hysteresis bands is a significant advancement in motor control strategies (Jiang and Zhou, 2016; Kadum, 2020). This approach ensures that the errors in flux and torque are maintained within predefined limits, enhancing performance and efficiency (Yin *et al*., 2019). Moreover, the integration of FLC allows for adaptive control, which can adjust to varying operating conditions and load disturbances, further improving the robustness of the system (Rehiara *et al*., 2017). Yao *et al*. (2016) proposed a method in which the implementation of FLC mitigated torque and flux ripples, enhancing response dynamics. Furthermore, it diminished the settling time of the system (Tokui *et al*., 2021; Manivasagam *et al*., 2024). The hysteresis-based control methods provide significant advantages; however, they may also introduce complexities in implementation and require careful tuning to optimize performance across varying operational conditions (Behloul *et al.,* 2022; Haq and Okumus, 2020).

Abdullah *et al*. (2022) proposed a cost-effective digital RPM meter. It monitors and regulates motor speed; the system utilizes Bluetooth technology via mobile devices. Induction motors operate on alternating current (AC) lines, with power intake influencing rotational speed (Afzeri *et al*., 2023; Paramo-Balsa *et al*., 2021). The AC driver circuitry enables modulation of AC line power for induction motor speed adjustment.

An Atmega family microcontroller generates PWM signals for an opto-coupler, which actuates the TRIAC, supplying power to the induction motor (Bahade *et al*., 2024). The microcontroller receives instructions via a mobile phone connection to the system. The mobile phone sends DTMF signals to the system, which the system recognizes and responds to appropriately (Rahul *et al*., 2022; Kumbhar, 2014). A button increases induction motor speed, another alters direction, and a third decreases speed (Rakib *et al*., 2022). This ongoing research illustrates the operational principles of a Digital Tachometer. To facilitate the observation of motor velocity, it employs a Digital Tachometer framework as a preliminary model. Furthermore, it enhances security measures and simplifies the process of modifying motor speed (Ehikhamenle and Omijeh, 2017). The integration of these components ensures efficient operation and enhances the overall performance of the motor control (Sakai and Hideaki, 2020)

Ankarao *et al*. (2017) presented a novel robust control scheme utilizing three first-order auto-disturbance rejection controllers for induction motor speed control. The dynamic performance of the induction motor is compared using ADRC and FUZZY controllers ("An Implementation of Soft Computing Approach," 2022). Conventional PI controllers face issues due to induction motor parameter mismatch or temporal variation (Alawan *et al*., 2019). Furthermore, the occurrence of load disturbances is frequently accompanied by an extensive recovery duration (dos Santos *et al.,* 2021). This extended recovery duration may result in elevated operational expenditures and diminished efficiency within systems that depend on stable performance (O'Connell, 2017). In these instances, the rotor flux estimator necessitates increased memory and runtime (Mahsahirun *et al.,* 2020). A novel control strategy employing three first-order auto disturbance rejection controllers is implemented for robust speed regulation of induction motor drives (Chalawane *et al*., 2017). The induction motor's speed variations are analyzed through adjustments in parameters such as rotor resistance and load conditions from no load to full load (Cherifi and Miloud, 2017). The rotor resistance is adjusted incrementally utilizing the ADRC and fuzzy controllers (Chacko *et al*., 2016; Al Zabin and Ismael, 2019). The system's operational performance is analyzed across multiple scenarios to evaluate the success of the suggested control strategy in ensuring speed and stability (Liu *et al*., 2023). The results indicate that the ADRC controller outperforms the fuzzy controller in terms of response time and stability, particularly under dynamic load conditions (El-Sehiemy, 2022). The results indicate that the proposed control strategy significantly enhances the system's ability to adapt to disturbances, ensuring consistent performance across a range of operational scenarios (Jafari and Ioannou, 2022). However, the analysis reveals that the fuzzy controller outperforms the ADRC controller in terms of response time and precision, particularly under dynamic load conditions (Mansouri *et al*., 2020).

CONCLUSION

The review of various control techniques for induction motors reveals a spectrum of advantages and limitations. Although sophisticated techniques such as Active Disturbance Rejection Control (ADRC) exhibit potential in enhancing response times and system stability, conventional methodologies, including Proportional Integral (PI) control and scalar control, continue to be of considerable importance in less complex applications owing to their straightforward implementation and economic efficiency. The paper emphasizes the need for ongoing research to address the limitations of existing methods, particularly in enhancing adaptability and performance under dynamic conditions.

Future Recommendation

Future developments should focus on integrating smart technologies and advanced algorithms to optimize induction motor control, ensuring they meet the evolving demands of industrial applications while promoting sustainability.

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