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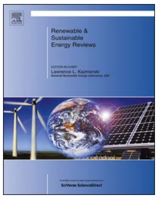

Optimization techniques to enhance the performance of induction motor drives: A review

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ABSTRACT

Induction motor (IM) drives, specifically the three-phase IMs, are a nonlinear system that are difficult to explain theoretically because of their sudden changes in load or speed conditions. Thus, an advanced controller is needed to enhance IM performance. Among numerous control techniques, fuzzy logic controller (FLC) has increasing popularity in designing complex IM control system due to their simplicity and adaptability. However, the performance of FLCs depends on rules and membership functions (MFs), which are determined by a trial-and-error procedure. The main objective of this paper is to present a critical review on the control and optimization techniques for solving the problems and enhancing the performance of IM drives. A detailed study on the control of variable speed drive, such as scalar and vector, is investigated. The scalar control functions of speed and V/f control are explained in an open- and closed-loop IM drive. The operation, advantages, and limitations of the direct and indirect field-oriented controls of vector control are also demonstrated in controlling the IM drive. A comprehensive review of the different types of optimization techniques for IM drive applications is highlighted. The rigorous review indicates that existing optimization algorithms in conventional controller and FLC can be used for IM drive. However, some problems still exist in achieving the best MF and suitable parameters for IM drive control. The objective of this review also highlights several factors, challenges, and problems of the conventional controller and FLC of the IM drive. Accordingly, the review provides some suggestions on the optimized control for the research and development of future IM drives. All the highlighted insights and recommendations of this review will hopefully lead to increasing efforts toward the development of advanced IM drive controllers for future applications.

1. Introduction

Induction motors (IMs) are widely used in numerous applications and account for approximately 60% of the total industrial electricity consumption (including factories, industrial sectors, air compressors, fans, railway tractions, pumps, blowers, cranes, textile mills, electric home appliances, vehicles, modes of transportation, and wind generation systems) because they are dependent on the conversion of electrical to mechanical energy [1–3]. Moreover, IMs are easy to maintain due to their simple structure, reliability, high efficiency, and low cost [4–7]. The distinction of IM has led to its global increase in sales of up to 85% in electrical motors [7].

In the past, speed controls used in the DC motors drive because of their simple design in controlling flux and torque. However, DC motors are difficult to maintain, and they corrode and spark [3,8–10]. Then, AC motors have been used to replace DC motors; semiconductor devices, such as insulated gate bipolar transistor metal oxide semiconductor field-effect transistor, have been developed and improved [8–11]. In addition, the designs of AC motors use digital signal processor (DSP), microcontroller, and field programmable gate array to solve difficult and fundamental challenges [3,10–12]. However, the torque, flux, and speed controls of these IMs are difficult to control because of their complex design and nonlinear model [9,10,13,14]. Therefore, two main methods, namely scalar and vector control, have been developed to control the IM [1,3,4,7,13].

The scalar control method has been used in several studies because of its simple structure, low cost, easy design, and low steady-state error [1,3,4,13,15]. Moreover, it has the advantage of stability in controlling middle to high speed and does not require the parameters of an IM [16]. This method has been used by many researchers in controlling IMs (using DSP) [1,4,17–21], single- [22] and five-phase IMs [27], and permanent magnet synchronous motors (PMSMs; using DSP) [23–26].

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Conversely, the vector control method is the most commonly used control scheme in previous research because of its high performance in controlling IMs [9,10,13,28,29]. Its control principle is based on the magnitude of obtained amplitudes and frequency voltages in controlling IMs. Thus, the vector control is used in controlling the position of the flux, voltage, and current vectors [3,13,24]. However, it has the disadvantage of coupling between the electromagnetic torque and flux that leads to difficulty and complexity of the IM controller [3,10], and it is also affected by the sensitivity of IM parameters [3,28,30]. This first problem can be solved through field-oriented control (FOC) and direct torque control (DTC) [26,28,29,31]. FOC consists of two control techniques, namely direct FOC (DFOC), which was proposed by Blaschke in 1972 [32], and indirect FOC (IFOC), which was proposed by Hasse in 1968 [33]. FOC has been used in several studies because of the high performance of controller in IM drives. DFOC and IFOC aim to obtain torque and flux decoupling even with their complex mathematical equations for IM. These methods have been used by numerous researchers in several applications [3,7,10,14,15,30,31,34–38].

Many control schemes are used to control the IM drive system. Among such schemes are the conventional controllers, namely, proportional–integral–derivative (PID) control, proportional–integral (PI) control, and proportional–derivative control. These conventional controllers were proposed by Taylor Instrument Company in 1936 [39]. PID is considered a good control technique because of its easy to use design, low cost, and simple structure; thus, it is utilized in numerous applications along with scalar and vector techniques [38,40,41]. PID controller is also used in regulating main variables, such as voltages, currents, speed, torque, and rotor flux in IMs [42]. However, the parameters for PID controller, namely proportional gain (kp), integral gain (ki), and derivational gain (kd), are difficult to obtain. These parameters play an important role in model control in terms of sensitivity and stability [16,30,38,43,44]. Therefore, PID control parameters should be suitable with sudden changes in speed or mechanical load [16]. The coefficient of PID controller can be identified using several methods, such as Ziegler–Nichols (Ziegler and Nichols, 1940) [45], Cohen–Coon (1953), Lambda tuning method (Dahlin, 1968) [46], and visual loop tuning method. These methods, however, experience process upset, undergo trials and errors, and require several calculations and mathematical models [47–49].

The fuzzy logic controller (FLC) was proposed by Zadeh in 1965 [50]. Recently, it has been used due to its adjusted online control according to adaptive modeling with sudden event changes in systems [14,51]. Moreover, FLC does not require an exact mathematical model; it can handle both linear and non-linear systems; and it is based on linguistic rules, which is the basis of human logic [30,44,52–55]. Therefore, FLC has become increasingly popular in designing the control systems of several models, such as in Refs. [1,16,56–59]; it was used to improve the control for the scalar speed control of IMs. In Refs. [14,30,36,52,60–63], FLC was used to develop the vector control for IM. In Refs. [60,64,65], FLC was used to control the variable speed of wind turbine based on dual star induction generator. FLC was also used in Ref. [66] to provide optimal control for the voltage and frequency of an AC microgrid. In Refs. [67,68], FLC was used to improve the sensorless stator FOC on an IM. FLC was also used to control a five-phase IM [69].

Pulse width modulation (PWM) techniques for driving three-phase voltage source inverter (VSI) play an important role in controlling IMs by dominating the switching devices [49,58,70–72]. Therefore, the main principle of VSI is to regulate the AC output voltage and frequency from a constant DC supply voltage. Moreover, PWM techniques develop the output waves of the inverter for high efficiency, low distortion, minimized harmonics, less switching loss, easy implementation, and less computation time [54,55]. Sinusoidal PWM (SPWM) is a PWM method in which the reference modulation wave is compared with a triangular carrier wave, and the intersections define the switching instants. Within every carrier cycle, the average value of the output voltage becomes equal to the reference value; SPWM is also a simple and easy structure [73,74]. Space vector PWM (SVPWM) is one of the most popular PWM technique that has recently gained interest among researchers. Meanwhile, the hysteresis band PWM (HBPWM) and random PWM (RPWM) reduce switching losses and harmonics, respectively [19,27,49,71,73,75]. In Ref. [76], Piao and Hung reported a unified SVPWM technique for a multilevel inverter that requires complex nonlinear calculation involving modulation implicit functions of SVPWM. In general, most of the SVPWM requires complex online computation which leads to difficulty in real time implementation. Thus, the conventional SVPWM requires additional memory that limits the choices of switching frequency and thereby reducing the accuracy of SVPWM [77,78]. To solve this problem genetic algorithm (GA) based SVPWM is utilized [79], but the GAs requires much iteration to find the best results, which is time consuming. An artificial neural network (ANN) is also used in SVPWM [77,78] for efficient inverter operation. In Refs. [80–82], the adaptive neural fuzzy inference system (ANFIS) based SVPWM is used for the two-level inverters. Moreover, optimized hybrid modulation strategies based on multiple divisions of active vector time and control are utilized to improve the harmonic elimination performance, reduce switching losses and current ripples of the IM drive [83,84]. However, the above-mentioned methods encountered problems because of their huge data requirement, long training, and learning times of linear and nonlinear functions that consume huge memory for real-time implementation. In Ref. [85], a random forest (RF) regression based implementation of space vector pulse width modulation (SVPWM) for two-level inverter is utilized using BSA optimization to improve the performance of the IM drive over conventional schemes in terms of damping capability, settling time, steady-state error, and transient response under different operating conditions.

Computational intelligence optimization algorithms are nature-inspired computational methodologies that address complex real-world problems. These algorithms can be divided into swarm intelligence methods and evolutionary algorithms (EAs). Swarm intelligence optimization algorithms generally use reduced mathematical models of the complex social behavior of insects or animals. The most popular swarm intelligence methods are particle swarm optimization (PSO) [86], artificial bee colony (ABC) [87], and ant colony optimization (ACO) [88]. The PSO mimics the movements of bird flocking or fish schooling [89]. The ABC method is inspired by the food-searching mechanism of honeybees and uses the foraging behavior of these insects [87]. Meanwhile, ACO was developed based on the behavior of ants when searching for the optimal path between their colony and food source [88]. EAs derive their working principles from natural genetic evolution. At each generation, the best individuals of the current population survive and produce offspring that resembles them; hence, the population gradually comprises enhanced individuals. Operations, such as recombination, crossover, mutation, selection, and adaptation, are involved in the EA process [90]. Popular EA paradigms are the genetic algorithm (GA) [91], evolutionary programming, differential evolution [92], evolutionary strategy, and genetic programming. These algorithms are based on the principles of Darwinian theory and other evolution theories of living beings. Recently, a numbers of researches have been developed on multi-objective IM parameter estimation to minimize the error between the estimated and the manufacturer data using sparse grid optimization algorithm [93,94], BSA [55], explicit model predictive control via quadratic programming [95].

Many real-world optimization problems involve nonlinearities and complex interactions among problem variables, and therefore nature-inspired optimization techniques are applied to solve such problems. The problem-solving capacity of these techniques is generally achieved by modifying existing algorithms, hybridizing algorithms, and developing new algorithms. Several nature-inspired optimization techniques have been proposed to overcome the limitations of their predecessors. The following descriptions highlight the recent nature-inspired opti-