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Sensorless Stator Field Oriented-Direct Torque Control with SVM for Induction Motor based on MRAS and FLC

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ABSTRACT

This research is centred around enhancing the Direct Torque Control (DTC) methodology utilized in induction motor (IM) drives. This study incorporates Space Vector Modulation (SVM) as a means to mitigate the excessive torque/flux ripples and current distortion commonly associated with standard Direct Torque Control (DTC). The objective is to reduce these undesirable effects while maintaining a consistent switching frequency. Furthermore, the conventional proportional-integral (PI) controllers will be substituted with Fuzzy Logic Controllers to effectively govern the stator flux and torque. This substitution aims to achieve accurate reference tracking and a resilient response to various uncertainties, including external disturbances and parameter fluctuations. Furthermore, a sensorless methodology referred to as stator flux based Model Reference Adaptive System (SF-MRAS) has been devised to facilitate the estimation of rotor speed. The utilization of this estimator has promise for enhancing the reliability of the controlled system, while concurrently reducing the expenses associated with the speed sensor. Consequently, the system's performance can be enhanced. A comprehensive investigation of the global control technique was conducted by employing Matlab/Simulink in conjunction with a dSpace 1104 signal card. This investigation encompassed both numerical simulation and real-time experimentation.

KEYWORDS: Induction Motor, Fuzzy Logic Controller (FLC), Direct Torque Control (DTC), Stator Flux Model Reference Adaptive System (SF-MRAS), Space Vector Modulation (SVM).

1. INTRODUCTION

The proposal of Direct Torque Control (DTC) aimed to replace Field Oriented Control (FOC)within the drives domain, with the objective of establishing a more efficient and independent control of electromagnetic torqueand flux. This action was undertaken with the aim of attaining an optimal management of these two variables.The Direct Torque Control (DTC) method exhibits superiority over the Field-Oriented Control (FOC) approach due to its simpler operational scheme, quicker response time, and reduced reliance on the specific characteristics of the machine. Furthermore, it is worth noting that the aforementioned process does not require the alteration of coordinate systems or the adjustment of current flow [1]. Nevertheless, the main concerns associated with this technology are around the significant presence of fluctuations in flux and electromagnetic torque. These fluctuations arise from the variable switching frequency, which is a result of the discrete characteristics of the hysteresis comparators and the voltage vector selection process using a look-up table [2]. The observed ripples can be attributed to the variable switching frequency.

The space vector modulation (SVM) technique has been suggested as a potential alternative to the conventional switching table employed for voltage vector selection, as evidenced by existing research. Maintaining a steady switching frequency has the potential to significantly mitigate the disturbances in both flux and torque [3]. The focus of this study will be on the SFOC-based SVM-DTC method, as discussed in reference [4]. Unfortunately, individuals utilizing PI controllers are obligated to possess a specific expertise in the modelling of control systems. Furthermore, it should be noted that PI controllers exhibit limited performance, particularly in the presence of disturbances and uncertainties. Selecting suitable gains for these controllers is a complex task, especially in real-world scenarios. Consequently, the global system may experience effects on both its dynamic andstable components. The typical approach to determining the motor's parameters involves the utilization of experimental methods, which unfortunately introduces the possibility of measurement errors that cannot be entirely eliminated.

Several control systems have been devised to address the limitations mentioned, including variable structure Sliding Mode Control (SMC), Model Reference Adaptive Control (MRAC), and artificial intelligent techniques [5]–[7]. The combination of fuzzy logic controllers (FLC), commonly referred to as FLC, with the Direct Torque Control (DTC) method has been seen in several studies [5, 8]. Even in the absence of prior familiarity with the control system model, individuals are capable of delivering satisfactory responses and achieving precise tracking. Consequently, the conventional PI controllers will be replaced by these novel controllers in the context of flux and torque regulation.

Furthermore, the primary aim of this study is to eliminate the utilization of a mechanical sensor and substitute it with a soft sensorless algorithm. This substitution is intended to reduce the overall cost of the system and enhance its reliability, as indicated by previous research [9]. The reconstruction of flux and rotor speed has been extensively studied in several scholarly publications that have been suggested [10][4]. The Model Reference Adaptive System method has gained significant popularity due to its inherent simplicity. Various MRAS structures have been documented in the existing literature (11–13). The rotor flux model reference adaptive system (MRAS) method, commonly referred to as the rotor flux MRAS [14], is widely employed in practice. This work introduces an alternative MRAS estimator that utilizes the stator flux model. In the context of stator field oriented SVM-DTC control design, the utilization of the stator flux model reference adaptive system (SFMRAS) is deemed to be a more advantageous option. The omission of the rotorflow estimation phase in the observer of the reducer introduces additional complexity.

Direct torque control (DTC) is a control methodology employed in the regulation of electric motors. The utilization of this form of control has several advantages, such as a clear and organized framework, efficient separation of components, and a timely response. Nevertheless, the operational efficiency of the controlled machine is compromised due to the presence of fluctuating frequency, substantial ripples, and harmonics, which can be attributed to the utilization of hysteresis comparators [1]. In the present setting, the emergence of these control techniques has garnered significant attention from researchers. The present study introduces a proposed method, referred to as pulse width modulation-based direct torque control with constant switching frequency (SPWM-DTC), as documented in reference [2]. The proposed control mechanism would serve as a substitute for the conventional switching table employed in typical Direct Torque Control (DTC) systems. The SPWM-DTC technology has reduced levels of harmonic distortion, diminished ripple effects, and negligible losses associated with switching when compared to other analogous technologies. Nevertheless, the efficacy of this method, which relies on linear proportional-integral regulators, cannot be assured in the face of diverse external disturbances, parameter variations, and significant non-linear coupling among the machine variables [3]. The utilization of modern mathematical techniques has facilitated a groundbreaking advancement in the field of robust and non-linear control methodologies. These approaches aim to address the limitations of linear controls in electric motors. The advancement described above was facilitated through the use of contemporary mathematical methodologies. The model predictive control (MPC) technique has garnered attention from numerous academics in the field of electric motor driving as a non-linear strategy of interest. The fundamental idea of Model Predictive Control (MPC) involves theutilization of a dynamic model of the controlled process within the controller itself. This allows for the anticipation, in real-time, of the future behaviour of the process [4]. The achievement of this objective is facilitated through the utilization of a dynamic model of the process under control. Nevertheless, the utilization of this technology is limited as a result of the intricate nature of legal regulation and its subpar performance in a stable condition [5]. The Backstepping approach is a method employed to achieve system stabilization by the systematic synthesis of regulators, utilizing Lyapunov's theory in conjunction with an adaptive model. The methodology in question is expounded upon in reference [6], and it has been endorsed by said source. Despite its high level of precision, this technique lacks the necessary sensitivity to adequately account for the uncertainties associated with the parameters [7]. Sliding mode control, also referred to as SMC, is a robust and non-linear methodology that has been devised to enhance conventional direct torque control (DTC) methods. The system is characterized by its exceptional dynamic performance and robustness against disruptions and alterations in its regulating parameters [8]. The occurrence of the "chattering" phenomenon, resulting in the generation of high harmonics, represents an undesirable limitation of this technology, hence restricting its applicability across several practical domains. Artificial intelligence methodologies, such as fuzzy logic control (FLC) and artificial neural network (ANN), have emerged as potential solutions for addressing nonlinear control problems in recent times [9]. These strategies possess the capacity to address the aforementioned challenges. Several research, including reference [10], have suggested integrating Direct Torque Control (DTC) with Artificial Neural Networks (ANN). This integration involves substituting the hysteresis comparators and switching table of DTC with a technique derived from ANN. However, in order to do this subsequent operation, it is imperative that the processors involved possess the capability to executeparallel processing. Furthermore, the establishment of an appropriate network architecture necessitates the execution of numerous iterations, as the formulation of an Artificial Neural Network (ANN) lacks a specific criterion. The execution of such a command is prohibited due to this specific reason. The FLC possesses the capability to effectively handle systems that are either highly complex or inadequately modeled. Furthermore, the functioning of the system is reliable, exhibiting a little mathematical reliance on various installation conditions [11]. In the field of direct torque control (DTC), the conventional switching table and hysteresis comparators have been substituted with a fuzzy switching table that operates on a fuzzy logic framework. The application of linguistic principles pertaining to fuzzy decision tables is employed in the development of switching laws for two-level inverter circuits [12]. The design of the fuzzy logic controller does not require a precise mathematical model of the system and is capable of accommodating any nonlinearities or uncertainties that may develop. In comparison to alternative artificial neural network systems, the FLC exhibits prominent advantages, namely the decreased processing time needed for operations and the uncomplicated building of the control mechanism.

STRUCTURE OF PAPER

The paper is organized as follows: In Section 1, the introduction of the paper is provided along with the structure. In Section 2 we discuss Literature review. In Section 3 we have discussed about Induction motor. Section 4 shares information about the SFO-SVM DTC Control Startegy. Section 5 tells us about the Fuzzy Logic Controller. Section 6 shows the simulation results and concludes the paper with acknowledgement and references.

2. LITERATURE REVIEW

The adoption of field-oriented direct torque control (FO-DTC) is increasingly prevalent in the industrial sector as the preferred method for regulating the torque output of induction motors. The title of the research paper is "Sensorless Stator Field Oriented-Direct Torque Control with Space Vector Modulation for Induction Motor based on Model Reference Adaptive System and Fuzzy Logic Regulation". The work presented at the 6th International Conference on Systems and Control (ICSC) in 2017 was authored by Abdelkarim Ammar, Amor Bourek, Abdelhamid Benakcha, and Tarek Ameid. To mitigate the disturbances caused by frequency switching, the authors of this paper employ the technique of space vector modulation.The scholarly publication titled "FOC and DTC: Two Viable Schemes for Induction Motors Torque Control" was authored by D. Casadei, F. Profumo, G. Serra, and A. Tani. It was published in the IEEE Transactions on Power Electronics, namely in volume 17, number 5, spanning pages 779 to 787, in the year 2002. The objective of this study is to make a scholarly contribution by conducting a comprehensive assessment of two distinct control techniques, focusing on their individual advantages and disadvantages.The article titled "Simple Flux Regulation for Enhancing State Estimation at Extremely Low and Zero Speed of a Speed Sensorless Direct Torque Control of an Induction Motor" was authored by I. M. Alsofyani and N. R. N. Idris. It was published in the April edition of IEEE Transactions on Power Electronics, specifically in volume 31, number 4, spanning pages 3027–3035. This study introduces a straightforward method for regulating flux in the context of direct torque control (DTC) applied to an induction motor (IM). The objective of this rule is to enhance the accuracy of speed and torque estimations in areas characterized by low and zero velocities.

The recent study aims to develop and implement an advanced predictive torque control system for the control of induction motor drives. This is achieved through the use of multi-objective fuzzy decision-making services, finite control set model predictive control (FCS-MPC), and the Kalman filter technique. The primary objective of this system is to facilitate optimal performance and expedite dynamic processes. There is a proposal to utilize an advanced sensorless Model Predictive Torque Flux Control (MPTFC) in order to address the issue of significant torque fluctuations that are directly caused by model predictive torque control (MPTC). An unique modification was made to the adaptive full-order observer (AFOO) and this modification formed the basis for the control technique that was proposed in thisstudy. Furthermore, the suggested observer for the IM incorporates the issue of core loss and includes a compensation term to account for this loss. Furthermore, a new criterion known as the loss minimization criterion (LMC) has been introduced. The application of this criterion has been shown to mitigate the adverse consequences of instantaneous moment (IM) losses, particularly when implemented under conditions of moderate velocities and minimal loads. This article presents a comprehensive overview of the research conducted on several voltage control (VC) methodologies and optimization strategies implemented in induction motor (IM) drives, with the aim of achieving optimal system performance. Furthermore, apart from serving as a means to assess the latest advancements in the field, it can also prove beneficial for researchers and engineers to incorporate into their routine practices.

3. INDUCTION MOTOR

When the electric current in the rotor that is required to produce torque is produced through electromagnetic induction from the magnetic field of the stator winding, the type of electric motor that is being used is known as an induction motor or an asynchronous motor. Alternating current, or AC, electric motors are also referred to by these names. There is another name for induction motors, and that is the asynchronous motor.[1] Because of this, it is possible to build an induction motor even if there will be no electrical connections made to the rotor during the process. The rotor of an induction motor can either be of the winding kind or the squirrel-cage type. Both configurations have their advantages and disadvantages.

Drives in industrial applications are usually three-phase squirrel-cage induction motors because of their low cost, great dependability, and self-starting characteristics. Additionally, these motors are frequently employed in industrial applications. For lighter loads, such as those produced by garbage disposals andother stationary power tools, it is usual practice to deploy single-phase induction motors. This is because single-phase induction motors have a lower starting current. Although single- and three-phase induction motors have historically only been used for services requiring a single speed, these types of motors are increasingly being placed in applications requiring various speeds with the use of variable-frequency drives, or VFDs. VFDs offer particularly substantial prospects for reducing energy consumption in settings that have a variable load, such as those seen in applications involving fans, pumps, and compressors. These opportunities are particularly significantfor both currently available and potentially future induction motors.

It wasn't until 1824 that the French physicist Francois Arago came up with the idea of rotating magnetic fields for the first time. This idea is now often referred to as Arago's rotations. This was shown by Walter Baily in the year 1879, and it became the first induction motor of its kind as a result of him manually turning on and off switches.

Ottó Bláthy, an engineer from Hungary, is credited with designing the first commutator-free single-phase AC induction motor. He did this by eliminating the need for a commutator. Bláthy's invention, the electrical meter, was propelled by a single-phase motor, which Bláthy had built.[9][10]

Tesla is credited with the creation of the first AC commutator-free polyphase induction motors in 1885, whereas Galileo Ferraris is credited with the invention of the same type of motor in 1887. Tesla demonstrated a functioning motor model in 1885, while Ferraris did the same in 1887. Both of the inventors arrived at the same conclusion on their own. Tesla filed applications for patents in the United States in October and November of 1887, and he was granted a number of these patents in May of 1888. Tesla was a pioneer in the electrical industry. The research that Ferraris had undertaken on his AC polyphase motor and hadpresented to the Royal Academy of Science in Turin was published in April of 1888. Ferraris had submitted his findings to the academy. The fundamentals of how motors work were broken out in this piece of study.

In the year 1888, George Westinghouse, who was at the time working on constructing an alternating current power system, was granted a license to use Tesla's patents. Westinghouse was in the midst of developing an alternating current power system. Westinghouse also acquired an option to file for a patent in the United States on Ferrari's induction motor design.[17] In addition to this, Tesla provided consulting services for a period of twelve months. C. F. Scott, a worker at Westinghouse, was tasked with assisting Nikola Tesla and eventually took over responsibility for the creation of the induction motor at Westinghouse. This was after Tesla delegated the duty to Scott.[12][18][19][20] Both the cage-rotor induction motor, which was invented in 1889, and the three-limb transformer, which was invented in 1890, are credited to Mikhail Dolivo-Dobrovolsky. His advocacy for the advancement of three-phase technology remained unwavering throughout his career.[21][22] Additionally, he said that Tesla's motor was impracticable owing to two-phase pulsations, which motivated him to continue working on his three-phase ideas. Tesla's motor had two-phase pulsations.[23] Before B. G. Lamme invented a revolving bar winding rotor, the early Westinghouse motors had wound rotors and operated in two phases. These early Westinghouse motors were two-phase motors with wound rotors. Despite the fact that Westinghouse built its first functional induction motor in 1892 and created a series of polyphase 60 hertz induction motors in 1893, these early Westinghouse motors were two-phase motors.[12]

4. SFO SVM-DTC CONTROL STRATEGY

A. Stator field situated IM Model:The methodology employed in this study leverages the dynamic model of the acceptance machine inside the synchronous reference framework outlined by (d,q). The voltage model can be represented mathematically in equations (1) and (2) as.

$$\left.\begin{aligned} v_{sd} &= R_s i_{sd} + \frac{d\psi_{sd}}{dt} - \omega_s \psi_{sq} \\ v_{sq} &= R_s i_{sq} + \frac{d\psi_{sq}}{dt} - \omega_s \psi_{sd} \end{aligned}\right\} \quad (1)$$

$$\left.\begin{aligned} 0 = v_{rd} &= R_r i_{rd} + \frac{d\psi_{rd}}{dt} - (\omega_s - \omega_r)\psi_{rq} \\ 0 = v_{rq} &= R_r i_{rq} + \frac{d\psi_{rq}}{dt} + (\omega_s - \omega_r)\psi_{rd} \end{aligned}\right\} \quad (2)$$

B. SFOC Control outline: The stator field-introduction technique relies on the configuration of the motion vector in relation to the nearby d-pivot, while ensuring that the quadratic components of stator motion remain equal to zero.:

$$\psi_{sd} = \psi_s \; ; \; \psi_{sq} = 0$$

The prevailing consensus in the literature is that the d-pivot serves as the charging hub, while the q-hub functions as the torque hub (4). The voltage circumstances in synchronous edge can be expressed or conveyed as:

$$\left.\begin{aligned} v_{sd} &= R_s i_{sd} + \frac{d\psi_s}{dt} \\ v_{sq} &= R_s i_{sq} + \omega_s \psi_s \end{aligned}\right\} \qquad (4$$

The electromagnetic torque is:

$$T_e = P\psi_s i_{sq}$$

This computation implements stator transition and torque closed-loop control, employing Space Vector Modulation (SVM) to generate the inverter's control signals. In general, a pair of proportional-integral (PI) controllers are employed to obtain the transition and torque errors, which are then used to generate the voltage segments (Vsd, Vsq) in a synchronous reference frame [6]. The SVM unit will modify the reference voltages to generate the charge states of the inverter, transitioning them to stationary coordinates (α, β). The periodicity of the space vector modulation is constant, hence leading to a significant reduction in both torque and transition ripples.

5. FUZZY LOGIC CONTROLLER

Introduction:

The domain in which fuzzy set theory, fuzzy reasoning, and fuzzy logic are extensively studied and applied is commonly referred to as fuzzy logic control (FLC), which currently has significant research engagement. The utilization of FLC spans across diverse domains, encompassing industrial process control, medicinal instrumentation, and security applications. In contrast to conventional control techniques, fuzzy logic control (FLC) has demonstrated superior efficacy in addressing complex and ambiguous problems that can be effectively handled by a skilled human operator, even in the absence of prior knowledge of the underlying dynamics of the issue.

A control system refers to a configuration of tangible elements that is intentionally devised to modify a physical system in order to manifest preset desirable attributes within that system. Control systems can be classified into two distinct categories: open-loop control systems and closed-loop control systems. In control systems employing an open-loop architecture, the input control action is not contingent upon the real-time output of the physical system. Conversely, inside a control system including a closed-loop feedback mechanism, the input control action is contingent upon the output of the physical system. Control systems that function in a closed-loop manner are commonly known as feedback controlsystems.Inorder to effectively regulate any given physical variable, it is important to commence the process by conducting a measurement. A sensor collects data pertaining to the controlled signal. A plant can be regarded asan exemplification of a physical system that is subject to management. A closed-loop control system is distinguished by the property that the system inputs are determined by the responses generated by the system. The primary obstacle in upholding order can be articulated as follows:

By utilizing an error signal, it is possible to alter the output of the physical system under control. The error signal can be conceptualized as the discrepancy between the measured or computed actual response of the parameter and the desired or intended response. In order to get the necessary responses and characteristicsfor the closed-loop control system, it is possible to introduce an additional system, commonly known as a compensator or controller, into the loop. Figure 1 illustrates the fundamental block diagram of the closed-loop control system, serving as a point of reference. The fuzzy control rules can be reduced to their IF-THEN form, often known as the IE-THEN form.

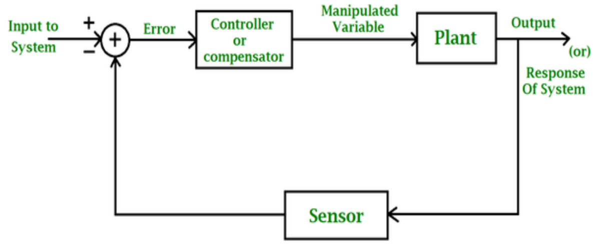


Fig 1: Block Diagram of closed-loop Control System

Control System Design:

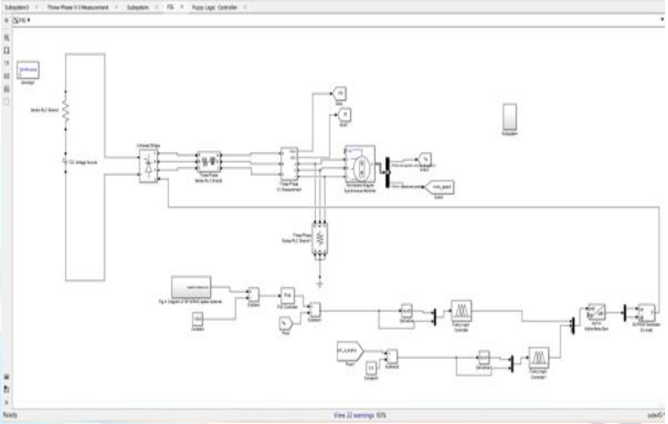
Designing a controller for a complex physical system involves the following steps:

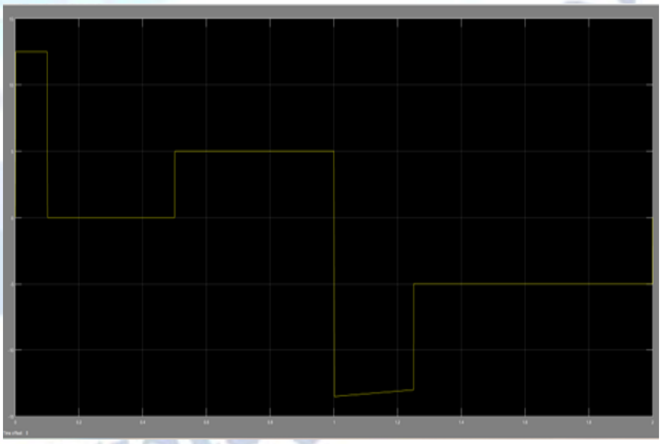
1. The process of breaking down the extensive system into a diverse set of subsystems.
2. One approach involves gradually altering the dynamics of the plant and then linearizing the nonlinear dynamics of the system around a specific set of operating points.
3. The task involves the arrangement of a collection of state variables, control variables, or output features pertaining to the system being examined.
4. The task at hand involves the design of uncomplicated proportional (P), proportional-derivative (PD), and proportional-integral-derivative (PID) controllers for the subsystems. It is also possible to create controllers that are optimal.

Apart from the initial four processes, there exists the potential for unpredictability arising from the contextual circumstances. Based on the control engineer's substantial knowledge and expertise, it is imperative to ensure that the design of the controller closely approximates the optimal practicable design. The achievement of this objective can be facilitated through the utilization of diverse numerical observations pertaining to the link between input and output. These observations may manifest as verbal, intuitive, or other forms of data pertaining to the dynamics of the plant and its surrounding environment. In summary,a supervisory control system, capable of both human and automatic operation, introduces an additional feedback control loop for the purpose of adjusting and modifying the controller's settings. This is performed to mitigate the variational impacts caused by nonlinear and remodeling processes. In contrast to the design principles employed in a conventional control system, the design of a fuzzy logic control (FLC) system necessitates the consideration of certain assumptions, should it be selected as the preferred approach. The plant under consideration should possess the capacity for both observation and management. There should be a diverse range of knowledge available, encompassing expert language rules, foundational engineering principles, input/output data sets, and a controller analytic model that can be fuzzified and utilized to construct the fuzzy rule base. The development of a fuzzy rule necessitatesthe completion of this condition. Furthermore, it is imperative that a pre-existing solution is available for the problem under consideration. This solution should be of a kind that enables the control engineer to pursue the attainment of a satisfactory outcome, rather than solely fixating on identifying the optimal solution. In this particular situation, it is important to fabricate the controller with utmost proficiency, ensuring that it adheres to an appropriate level of accuracy. It is imperative to emphasize that the challenges pertaining to stability and optimality persist as persistent concerns within the realm of fuzzy controller design.

6. SIMULATION RESULTS

Sensorless Stator Field Oriented-Direct Torque Control with SVM for Induction Motor Based on MRAS and Fuzzy Logic Regulation





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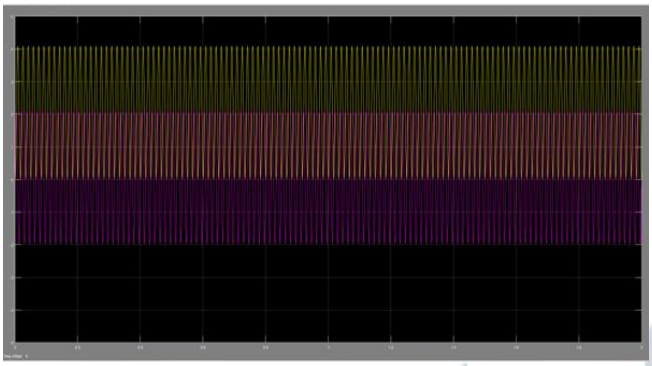
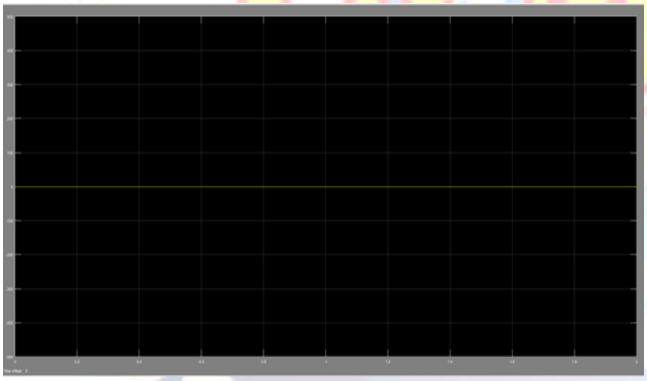


Flux components

Phisd



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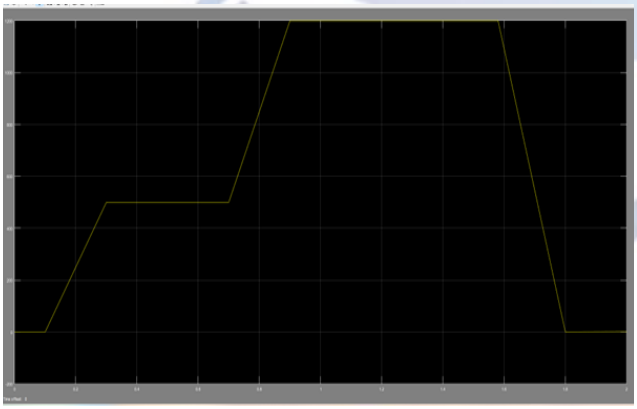

Rotor speed

7. CONCLUSION

This study focuses on improving the stator filed SVM-DTC for induction motor drives using fuzzy logic controllers and a speed MRAS observer. The decoupled FLC controllers for controlling stator flux and electromagnetic torque have been used togenerate the d and q components of reference voltages. This algorithm was developed with the intention of addressing many deficiencies and issues that are associated with DTC. The utilization of SVM offers a multitude of benefits, many of which have been validated through modeling and experimentation. Some of these benefits include good response, reduced ripples, low harmonics and a decent waveform of stator phase current, as well as steady switching frequency. The traditional PI controllers have been phased out and replaced with FLCs, which do not require the user to have prior knowledge of the mathematical model. This has been done in order to get better optimum performance. They have a more rapid dynamic, accurate tracking, and resilience against disturbances from the outside. In addition to this, the MRASobserver is capable of providing an accurate estimation in a variety of speed ranges, which helps to improve the reliability of the system by negating the need for a speed sensor. When driving an induction motor using SVM-DTC, the addition of intelligent controllers and sensorless observers can, in most cases, result in higher overall performance levels.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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