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Research Article

Fuzzy logic based High Speed SRM Using Vector Control for Electric Vehicle Applications

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Abstract

High-speed motors are essential for accomplishing the reduction in size of motors for electric vehicles (EVs). The Switched Reluctance Motor (SRM) is notable for its capacity in high-speed drives as a result of its uncomplicated and sturdy rotor configuration. Nevertheless, obstacles such as substantial vibration and acoustic noise, as well as the intricacy of traditional current excitation techniques, impede the development of an efficient torque controller. In order to tackle these problems, the use of vector control has been suggested for SRM drives. However, its utilization in the high-speed range has not been thoroughly investigated. This study examines the necessary driving conditions, such as switching frequency and bus voltage, for achieving effective functioning of a SRM in the high-speed range. The research shows that the suggested SRM may be efficiently operated utilizing fuzzy logic-based vector control in high-speed situations, resulting in decreased vibration levels. Fuzzy logic controllers (FLCs), renowned for their exceptional performance in intricate, non-linear, or ill-defined systems, are used to augment the control strategy. The controllers use fuzzy sets, facilitating a seamless shift from membership to non-membership, hence enhancing the overall performance of the system. The results emphasize the potential of using fuzzy logic-based vector control as a viable method to advance high-speed SRM technology in electric vehicle applications. This led to improved efficiency and decreased vibrations in electric propulsion systems.

Keywords— high-speed motors, Switched Reluctance Motor, vector control, fuzzy logic, electric vehicles, torque controller design

I. Introduction

The advancement of high-speed Switched Reluctance Motors (SRMs) using Vector Control for Electric Vehicles (EVs) is based on a significant past characterized by ongoing difficulties, clever advancements [1], and an unwavering quest for improved performance in the field of electric propulsion systems. This story takes place in the context of the rapidly growing electric car sector and the search for motor technologies that can meet the unique requirements of high-speed applications [2]. The beginning of this journey may be traced back to the realization of the crucial impact that high-speed motors might have in the field of electric cars. Researchers and engineers have explored motor technologies in order to downsize motors and optimize space and weight in Electric Vehicles (EVs) [3]. Out of all the candidates, the SRM [4] stood out as a viable choice because of its inherent simplicity and strong rotor structure. The early phase of study established the groundwork for a significant change in electric propulsion [5].

Nevertheless, the expedition was not devoid of its fair share of obstacles. The SRM, while showcasing promise for high-velocity propulsion, had challenges with vibration and auditory disturbance due to its distinctive driving mechanism. The usual techniques of current excitation, which are sophisticated and elaborate, further complicated the design of efficient torque controllers [6]. It became clear that a radical solution was necessary to fully use the capabilities of SRMs in high-speed applications for

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electric cars. The pivotal moment in this story occurred when the suggestion of implementing Vector Control for SRM drives was made. Vector control, an advanced control technique, offers a solution to the inherent difficulties of SRMs by giving a more refined and accurate method for current excitation. This marked the beginning of a new period in the pursuit of optimum SRM performance, leading to the development of enhanced control mechanisms and the reduction of problems caused by vibrations [7].

While establishing the theoretical basis for Vector Control in SRMs, researchers explored the complexities of drive conditions that would facilitate the effective use of high-speed SRM technology. Parameters like as switching frequency and bus voltage were identified as crucial factors that need careful consideration [8]. Investigating these circumstances proved a crucial stage in the trip, revealing the subtleties of high-speed SRM functioning and offering vital insights into the complexities of their drive. In the next stage of the story, there was a coming together of theoretical understandings and actual implementations. The development of the high-speed switched reluctance motor (SRM), using Vector Control, began in laboratory environments. The experimental verification of the operating circumstances and the effectiveness of the Vector Control technique were a noteworthy achievement [9]. It was discovered that the SRM, when exposed to the precisely adjusted Vector Control in areas with high speeds, not only successfully addressed the issues of vibration but also exhibited an impressive ability to operate with little vibration.

II. LITERATURE SURVEY

Electric vehicle applications of Switched Reluctance Motor (SRM) drive control were proposed by Rekha, P. S., and colleagues [10]. A Simulink model to recreate the SRM drive system and an electric vehicle control scheme were also created. The study addressed torque ripple reduction and control optimization to increase electric vehicle SRM drive performance and efficiency. However, limited experimental validation and the requirement for real-world testing to assess the control approach's practicality were drawbacks. Ajamloo, Akbar Mohammadi, Mohamed N. Ibrahim, and Peter Sergeant designed, modeled, and optimized a high power density axial flux SRM for electric automobiles [11]. Each was accountable for the task. The technique included finite element analysis, optimization, and experimental validation. The project aimed to improve motor performance by minimizing torque ripple. The dependence on optimization methods and the requirement for comprehensive testing under various operating conditions limited the reliability of the assessment.

Jasim, Ahmed Fawzi, Fadhel A. Jumaa, and Ali A. Abdullah Albakry [12] examined the effects of intelligent control approaches for SRM in electric vehicles. Several controllers were deployed and evaluated using computer simulations. Lack of comprehensive experimental validation and consideration of real-world operational conditions were study flaws. The research was limited, but it gave important insights on intelligent control. Bhim Singh, Gurmeet Singh, Kumar, and Arjun Singh [13] proposed a modified direct torque control for solar-fed sensorless SRM drives in electric automobiles with regenerative braking. Electric cars would utilize this control. The approach needed algorithm development and simulations to test the control algorithm's performance. The recommended control mechanism needed further experimental validation to prove its usefulness in various operating conditions. One drawback was this.

Dejamkhooy and Ahmadpour investigated how position sensor-less SRMs in electric automobiles reduce torque ripple [14]. The method included mathematical modeling, simulation study, and experimental validation. However, more rigorous testing was needed to account for a range of operating scenarios and practical implementation challenges. Ge, Lefei, and others [15] proposed a composite model predictive control method for SRMs using PWM-based signals to eliminate torque ripple. A composite model predictive control approach was built and simulated to evaluate its performance. The control method's complexity and the necessity for dynamic experimental verification were limitations. Using a new multilayer converter with minimum torque ripple, Cai, Yan, and colleagues [16] developed direct instantaneous torque control for SRM machines. The technology

included direct immediate torque control and a novel multilayer converter. The lack of experimental validation and inability to account for real-world operational conditions were drawbacks.
Sehab, Rabia, Ahmad Akrad, and Yakoub Saadi [17] proposed super-twisting sliding mode control to improve switching reluctance machine performance and robustness in electric vehicle drivetrain applications. The super-twisting sliding mode control algorithm proposed for the technology was tested using simulations. Experimental validation and practical application concerns were limits. Liu, Peilin, and colleagues [18] focused on SRM-powered electric vehicle parking control optimization. The approach included determining the best parking control system and simulating its effectiveness. Experimental validation and limited evaluation of real-world parking situations were disadvantages. Deepak, M., et al. [19] introduced updated model predictive direct torque control of SRM drive. This torque ripple-reducing control used a unique modified switching mechanism. The methodology employed model predictive control and performance simulations. Experimental validation and consideration of real-world operating conditions were constraints. Kumar, Arjun, and Bhim Singh [20] studied magnetic characteristics-less position sensorless SRM drive control for light electric automobiles. The aim was a wide speed range for the drive. The method involved position sensorless control algorithm design and performance assessment simulations. A constrained experimental validation and the necessity for further testing under varied operating conditions were limitations.

III. PROPOSED SYSTEM MODEL

Figure 1 illustrates the complexities of the vector control system used in the driving of Switched Reluctance Motors (SRMs). This schematic diagram serves as a visual guide, offering a complete understanding of the main elements and their interactions inside the vector control system. The virtual rotor flux (Φr) is a critical metric obtained from the zero-phase current and serves as the foundation of the vector control system. The existence of this virtual rotor flux demonstrates the use of a synthetic magnetic field as a substitute for the actual rotor in the SRM, showcasing a unique method. The virtual rotor flux serves as a crucial component in the control system, acting as a dynamic and adaptable element that responds to variations in the zero-phase current.
The figure illustrates the key importance of the vector control block, which contains the algorithms and control methods that manipulate the virtual rotor flow and, as a result, affect the motor's performance. The vector control block serves as the coordinator, enabling a seamless interaction among the different components. The successive phases of the control system are driven by the outputs, which are controlled by the virtual rotor flow and other important factors. The incorporation of the d-q axis current components, id and iq, is crucial in determining the dynamics of the magnetic field in the Switched Reluctance Motor (SRM). The components derived from the input current and its decomposition play a role in generating the spinning magnetic field in the stator, which is essential for producing torque. The vector control system enables exact adjustment of the magnetic field in the SRM by controlling the variation of id and iq within specified limits.

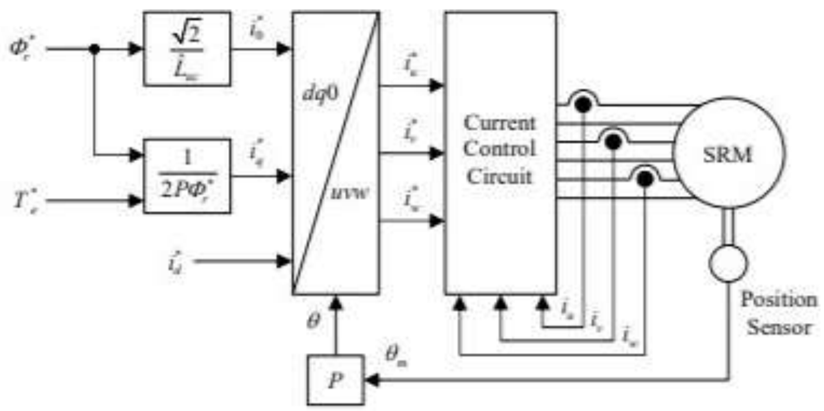

Fig. 1. Vector control system for SRM drive.

The torque controller, shown in the diagram, is another significant element of the vector control system. The controller is designed to accept inputs, such as the q-axis current (iq) and the virtual rotor flux (Φr), which provide real-time information on the motor's state. The torque controller acts as the central hub for decision-making, modifying the control inputs to maximize torque production while minimizing undesirable consequences like vibration and acoustic noise. The significance of this is crucial in attaining the delicate equilibrium necessary for effective and seamless motor functioning. The inclusion of the speed controller highlights the system's ability to quickly adapt to changing operating circumstances. The vector control system may adjust to variations in the motor's rotational speed by using speed feedback, often acquired via sensors. The speed controller optimizes the inputs to guarantee that the motor functions at the intended speed, showcasing the system's flexibility and effectiveness in practical situations. The current controller has great importance, since it has a crucial impact on the formation of the d-q axis currents. This component guarantees that the currents are adjusted to match the appropriate values, so maximizing the configuration of the magnetic field and, subsequently, the output torque. The present controller's capacity to effectively regulate the id and iq parameters significantly improves the stability and performance of the SRM.

A. Current controller for vector control

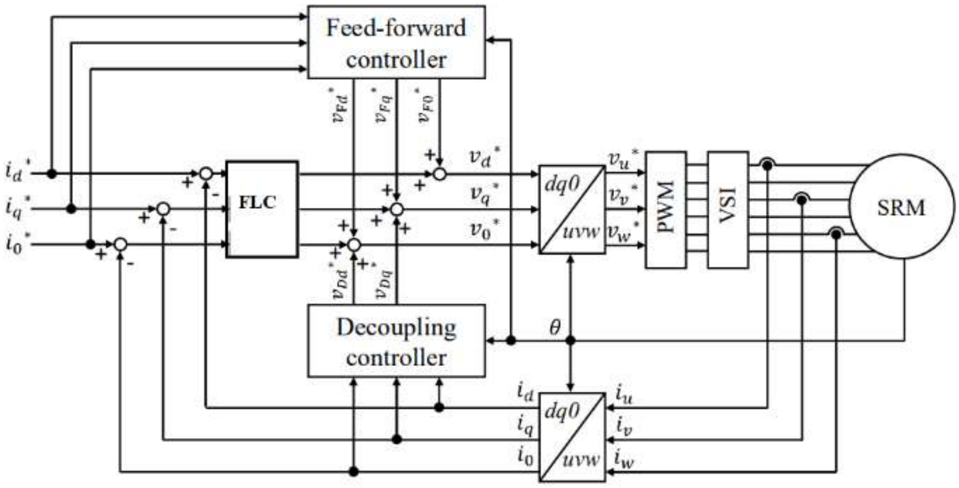

Fig. 2. Proposed FLC-Feed forward based Current Controller for Vector Control.

Figure 2 provides a detailed depiction of the present control architecture for vector control in switched reluctance motors (SRMs), showcasing a significant deviation from the traditional proportional-integral (PI) controller by using a fuzzy logic controller (FLC). This diagram illustrates three essential control components: the FLC (Fuzzy Logic Controller), the decoupling controller, and the feedforward controller. These components combined provide precise control over the current flowing through each axis and phase component of the SRM, allowing for the required motor performance to be achieved. The focal point of the control system is the Fuzzy Logic Controller (FLC), shown in the central position of the schematic. FLCs, in contrast to conventional PI controllers, use fuzzy logic to simulate decision-making processes that resemble those of humans. The FLC is specifically built to regulate the current on each axis and phase component. Its decision-making mechanism is intrinsically adaptive and can effectively handle the complex and nonlinear features of the SRM system. The capacity to adapt is especially beneficial in situations where accurate mathematical modeling may be difficult because of non-linearities in the system.

The decoupling and feedforward controllers are essential elements in improving the present control method. The decoupling controller maintains its essential role in untangling intricacies that arise from interactions among various axes and phase components. The feedforward controller anticipates disturbances, hence improving the system's ability to quickly respond to dynamic changes. The cooperative endeavors of these controllers enhance the resilience of the existing control system, reducing the difficulties related to cross-coupling effects and disruptions.

The control efforts culminate in the attainment of voltage instructions, which are then used to operate a carrier-based Pulse Width Modulation (PWM) inverter. The inverter, which is a component of the overall control system, converts the voltage instructions into tangible control signals for the SRM. The carrier-based pulse-width modulation (PWM) inverter enables a smooth transition from fuzzy logic control methods to actual motor control, enabling real-time modifications depending on received data. Equation (1) represents the transfer function of the FLC.

$$G_{PI}(s) = K_c\left(1+\frac{1}{\tau_c s}\right) \quad (7)$$

Here,

- $G(s)$ is the transfer function of the FLC.
- Kc is the gain of the FLC.
- τc is the time constant of the FLC.

In contrast to the conventional PI controller, the FLC transfer function employs the constants Kc and τc to denote the gain and time constant of the fuzzy logic controller, respectively. The decision-making process of the FLC incorporates language rules that encapsulate the expert knowledge or heuristics that regulate the control actions. The formulation of these rules is dependent on the fuzzy sets that have been specified for the input and output variables. The FLC evaluates linguistic variables, such as "error," "change in error," and "output," and constructs fuzzy sets for each variable. The decision-making process is guided by fuzzy rules that are stated in language terms. The FLC utilizes fuzzy inference to analyze the language inputs, which are then combined to provide a precise output that directly impacts the control action. The gain (Kc) and time constant (τc) in the transfer function of the FLC are adjusted according to the properties of the controlled system and the desired response. The FLC's flexibility and capacity to manage non-linearities make it highly suitable for systems with intricate and fluctuating dynamics. Integrating the Fuzzy Logic Controller (FLC) into the control architecture of the SRM system enhances the present regulation by introducing a more intelligent and context-aware approach. The FLC evaluates linguistic characteristics pertaining to the present mistake and the pace at which the error is changing, enabling it to adapt flexibly to different circumstances. The FLC's capacity to adjust to various operating circumstances makes it a potent substitute for conventional control schemes, particularly in systems characterized by non-linear and unpredictable dynamics.

B. Controllability of high speed drive

The assessment entails analyzing the current and torque waveforms at different switching frequencies to get a deeper understanding of the system's dynamic behavior. Equation (2) defines the metric of total harmonic distortion (THD) as a numerical measure of the harmonic content present in the current waveform. The Total Harmonic Distortion (THD) is determined by taking the square root of the sum of the squares of each individual harmonic current, which is then divided by the effective value of the fundamental current. The Total Harmonic Distortion (THD) metric is a measure of how pure the current waveform is. A lower THD value indicates a more sinusoidal waveform. Incorporating higher-order harmonics in the computation of total harmonic distortion (THD) allows for the measurement of the system's departure from an ideal sinusoidal waveform and offers significant insights about the present signal's quality.

In addition, Equation (3) introduces the idea of the current ripple ratio (CRR), which quantifies the variability in the current waveform. CRR is the ratio of the difference between the highest and lowest amplitudes of the current to the average current amplitude, expressed as a percentage. The CRR values provide valuable information on the stability and consistency of the current signal, where lower values indicate a more stable and regulated current profile. The efficacy of the control technique and the manageability of the high-speed drive system are shown by the manner in which these waveform metrics react to variations in switching frequency. To conduct a thorough investigation, it is necessary to consistently change the switching frequency and observe how this affects the overall harmonic distortion and current ripple ratio. This procedure enables the determination of the most favorable operating settings that strike a balance between the efficiency of the system and the presence of harmonic content. In addition, the assessment takes into account the influence of bus voltage on controllability. The bus voltage, a crucial factor in power electronics, impacts the whole energy conversion process and may greatly affect the system's controllability. The interaction between the frequency at which switches are toggled and the voltage at which the electrical power is distributed is crucial for establishing a well-balanced and effective functioning.

$$\mathrm{THD} = \frac{\sqrt{I_2^{\,2} + I_3^{\,2} + I_4^{\,2} + \cdots + I_n^{\,2}}}{I_1} \times 100[\%]$$

$$\mathrm{CRR} = \frac{i_{\max} - i_{\min}}{I_{ave}} \times 100[\%]$$

IV. Results and Discussion

Figure 3 presents a significant change in the control architecture by including a combination of a Fuzzy Logic Controller (FLC) and a Feed-Forward (FF) controller, known as FLC-FF controller. This model deviates from the traditional PI controller by including the adaptive and context-aware characteristics of FLC into the control method. The Simulink model demonstrates the incorporation of the FLC, a decision-making system that utilizes fuzzy logic principles to mimic human-like thinking. The FLC is intended to function with a Feed-Forward controller, which predicts and counteracts disruptions in the system. The model illustrates the intricate interaction among these controllers, the high-speed drive system, and the feedback loop. The FLC, which incorporates language rules and fuzzy sets, is designed to accommodate the dynamic and non-linear characteristics of high-speed drive systems. It offers a more sophisticated and adaptable control approach compared to the inflexible structure of a PI controller. The Feed-Forward controller enhances overall efficiency by anticipating the system's reaction and proactively changing the control signals. The system's predictive capabilities improves its capacity to manage sudden variations in operating circumstances, which are typical of high-speed drive systems. The adoption of the FLC-Feed Forward controller paradigm represents a shift towards more sophisticated and adaptable control techniques in the field of high-speed electric propulsion. The combination of fuzzy logic with feed-forward control recognizes the inherent intricacies and uncertainties in high-speed systems, providing a solution that can adaptively react to changing circumstances and disturbances. This Simulink model functions as a graphical depiction of the sophisticated control framework, offering a means to simulate and analyze the suggested control strategy for validation and optimization purposes.

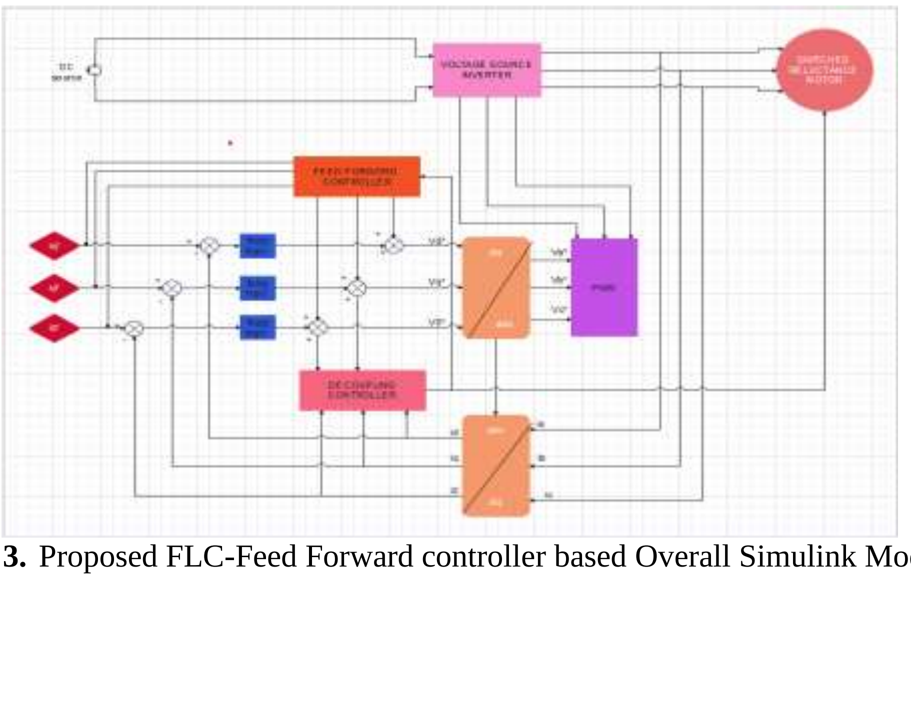

Fig. 3. Proposed FLC-Feed Forward controller based Overall Simulink Model.

Figure 4 presents the suggested waveform for the three-phase current in the high-speed drive system. Nevertheless, there is a significant decrease in the range of the electrical angle, which now spans from 0 to 0.14 degrees. This alteration proposes a more compact and presumably streamlined present profile. The sine wave maintains a constant amplitude, oscillating between positive and negative 130 Amps. The suggested current waveform is designed to meet the needs of high-speed applications, with the goal of preserving the dynamic and well-regulated character of the current. Additionally, it aims to enhance the system's reaction within a more limited electrical angle range.

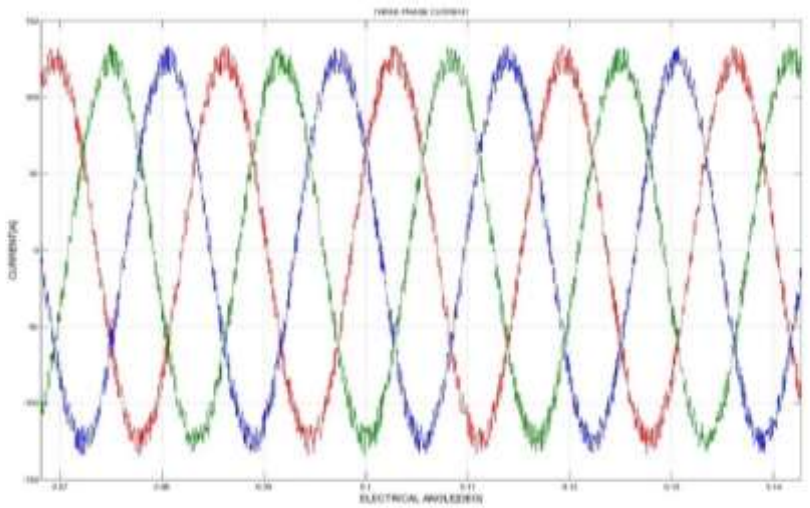

Fig. 4. Proposed Three Phase Current Response.

Figure 5 displays the suggested torque waveform, which exhibits a sinusoidal pattern similar to the current torque waveform. Nevertheless, a notable modification can be noted in the range of the electrical angle, which now spans from 0 to 0.1 degrees. This decrease implies a concentrated and perhaps more effective transmission of rotational force within a smaller range of angles. The torque waveform maintains a constant amplitude, fluctuating between 9 Nm and 21 Nm. The suggested torque profile aims to preserve the smooth and regulated torque production while perhaps enhancing the system's reaction within a narrower electrical angle. This aligns with the dynamic needs of high-speed drive systems.

Figure 6 illustrates the suggested d-axis, q-axis, and zero-phase currents in the high-speed drive system. Every individual electrical component displays a sinusoidal pattern, similar to the currents that already exist. Nevertheless, the most prominent modification is seen in the duration of the electrical angle, which has been decreased to 0.1 degrees. The d-axis current is set at a constant amplitude of 100 Amperes, the q-axis current is set at 60 Amperes, and the zero-phase current is set at 0.5 Amperes Nm. This change indicates a desire to simplify and maybe improve the existing components within a narrower electrical angle range, with a focus on accuracy and quick response in vector control.

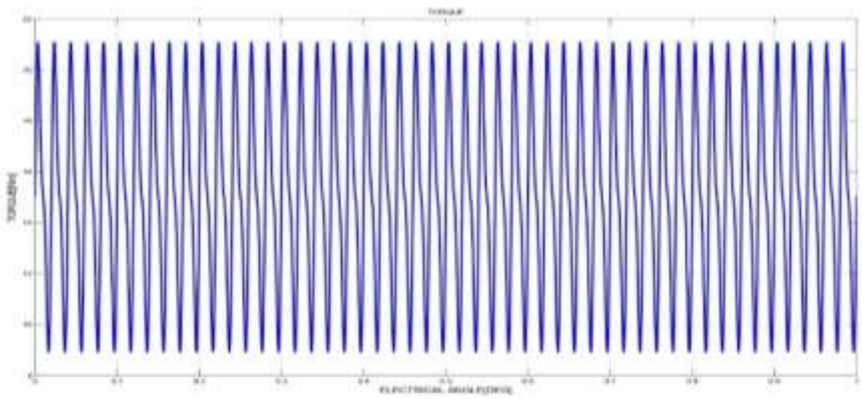

Fig. 5. Vector control system for SRM drive.

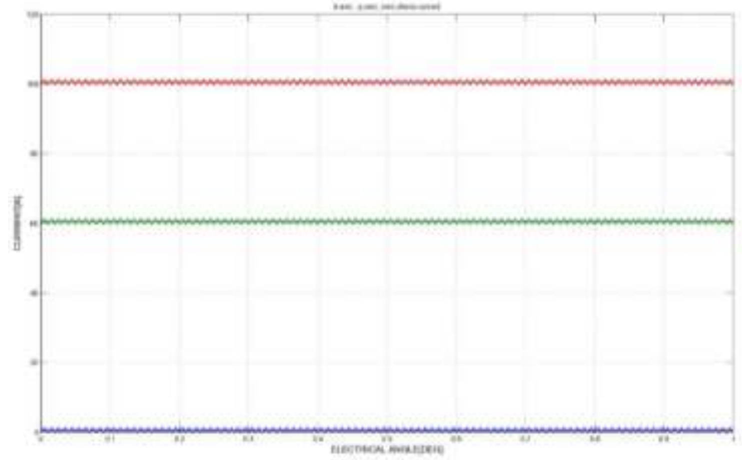

Fig. 6. Vector control system for SRM drive.

V. CONCLUSION

Integrating an FLC-FF into high-speed drive systems offers many benefits that significantly enhance the control and efficiency of the system. The main advantage of FLC-FF is its capacity to adapt to the complexities of intricate and nonlinear systems, making it particularly suitable for high-speed electric propulsion applications that include dynamic situations. FLC-FF stands out from conventional controllers due to its exceptional ability to manage uncertainties and imprecise data. It offers a reliable and steady reaction in practical situations when the dynamics of the system may not be accurately determined. The clearness of FLC-FF language rules enables easy adjustment by domain specialists, promoting a more profound comprehension of the control method. The software's capacity to effectively handle complex interactions between variables makes it particularly well-suited for high-speed drive systems, where motor responses may display sophisticated nonlinear features. The real-time flexibility of FLC-FF is essential for maintaining responsive control in dynamic settings, such as those seen in electric propulsion systems. The seamless and uninterrupted shift between operating areas, supported by FLC-FF, minimizes sudden changes that might jeopardize stability. Furthermore, by integrating expert information into the fuzzy rules, FLC-FF is able to use human intuition and experience, hence improving its performance. Essentially, the benefits of FLC-FF in high-speed drive systems result in a control strategy that is more adaptable, strong, and efficient. This makes FLC-FF a crucial component in the progress of electric propulsion technologies.

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