FUZZY LOGIC-ENHANCED VECTOR CONTROL FOR EFFICIENT SWITCHED RELUCTANCE MOTOR DRIVE IN ELECTRIC VEHICLES

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ABSTRACT

The demand for high-efficiency and high-performance motor drives in electric vehicles (EVs) has accelerated the adoption of Switched Reluctance Motors (SRMs) due to their robust construction, high-speed capabilities, and cost-effectiveness. However, controlling SRMs at high speeds presents challenges such as torque ripple, non-linear magnetic characteristics, and complex switching requirements. This paper proposes a Fuzzy Logic-Enhanced Vector Control (FLVC) strategy to improve dynamic performance and energy efficiency of SRM drives in EVs. The fuzzy controller adaptively tunes the vector control parameters based on real-time operating conditions, allowing smoother torque delivery and reduced electromagnetic noise. Simulation results demonstrate significant improvements in torque smoothness, speed tracking, and overall drive efficiency when compared to conventional control methods. The proposed control scheme shows strong potential for practical implementation in modern EV propulsion systems.

I. INTRODUCTION

Electric vehicles (EVs) are rapidly transforming the transportation industry, driving the need for efficient and reliable motor control strategies. Among various motor technologies, Switched Reluctance Motors (SRMs) have gained significant attention due to their rugged design, absence of permanent magnets, and suitability for high-speed operations. However, SRMs exhibit highly non-linear behavior, characterized by significant torque ripple and acoustic noise, which complicates their control—especially in the dynamic environment of EVs.

Traditional vector control methods, though effective for conventional motors, often fall short when applied to SRMs due to their variable inductance profiles and unaligned rotor design. To address these issues, intelligent control methods such as Fuzzy Logic Control (FLC) have been introduced. FLC is known for its ability to handle non-linearities and uncertainties without requiring a detailed mathematical model of the system.

This paper introduces a Fuzzy Logic-Enhanced Vector Control approach, which dynamically adjusts the vector control parameters in response to changing motor and load conditions. The integration of fuzzy logic into the control loop aims to improve torque response, minimize ripples, and enhance energy efficiency. The proposed methodology is particularly tailored for EV applications, where rapid acceleration, regenerative braking, and consistent performance are crucial.

II. LITERATURE SURVEY

The integration of advanced control strategies in switched reluctance motors (SRMs) has garnered significant attention in recent years, particularly for their application in electric vehicles (EVs). This literature survey reviews key studies that focus on the performance enhancement of SRMs through various control techniques, with a specific emphasis on fuzzy logic and vector control methodologies.

1. Switched Reluctance Motors in Electric Vehicles:

Research has established SRMs as a viable option for electric vehicle applications due to their inherent advantages, including high efficiency, robust design, and cost-effectiveness. According to Pillai et al. (2019), SRMs exhibit a favorable torque-to-weight ratio and can operate effectively in a wide range of speeds, making them suitable for EV propulsion systems. Their study highlights the growing interest in SRMs as manufacturers seek alternatives to traditional motor technologies like permanent magnet motors.

2. Control Techniques for SRMs:

The effective control of SRMs is crucial for maximizing their performance. Various control techniques have been explored, including direct torque control, field-oriented control, and sensorless control methods. However, these conventional methods often struggle to handle the nonlinearities and dynamic behavior of SRMs. A study by Sinha and Rathi (2020) emphasizes the limitations of traditional control strategies, noting that they may lead to torque ripple and efficiency losses, particularly under varying load conditions.

3. Fuzzy Logic Control in Motor Applications:

Fuzzy logic control (FLC) has emerged as a promising solution for addressing the nonlinearities in SRM operation. Research by Lee et al. (2021) investigates the application of FLC in controlling SRMs, demonstrating its effectiveness in managing torque and speed fluctuations. The authors propose a fuzzy logic-based controller that adapts to different operational scenarios, improving the overall performance and stability of the motor. Their findings indicate that FLC can significantly reduce torque ripple and enhance responsiveness during transient operations.

4. Vector Control Strategies for SRMs:

Vector control techniques have also been extensively studied for SRM applications, particularly due to their ability to decouple torque and flux control. In a review by Adnan et al. (2022), the authors highlight the advantages of vector control in achieving precise control over motor dynamics. Their research shows that implementing vector control can lead to improved efficiency and performance, especially in high-speed applications. However, the complexity of the control algorithms can pose challenges for real-time implementation.

5. Hybrid Control Approaches:

Several studies have explored the integration of fuzzy logic and vector control to capitalize on the strengths of both techniques. A notable contribution by Kumar and Patel (2023) proposes a hybrid control strategy that combines fuzzy logic for adaptive tuning with vector control for precise torque management. The results indicate that this hybrid approach yields superior performance compared to traditional control methods, achieving better torque response and overall system efficiency.

6. Future Directions and Challenges:

While significant progress has been made in SRM control strategies, challenges remain, particularly in terms of real-time implementation and scalability. Future research should focus on refining hybrid control algorithms, optimizing their performance under various operating conditions, and addressing the computational complexities associated with their application. Additionally, integrating machine learning techniques could further enhance the adaptability and efficiency of control systems for SRMs in electric vehicles.

In summary, the literature underscores the potential of advanced control strategies, particularly fuzzy logic and vector control, in enhancing the performance of switched reluctance motors for electric vehicle applications. These studies provide a solid foundation for ongoing research aimed at developing more sophisticated control systems that can effectively address the challenges associated with SRM operation. By synthesizing insights from various studies, this survey establishes a basis for the current research on fuzzy vector control in high-speed SRMs, contributing to the advancement of electric vehicle technologies.

III. DC-DC CONVERTERS

Applications for this high-voltage step-up DC-DC converter include battery backup systems for uninterruptible power supply, fuel cell energy conversion systems, solar-cell energy conversion systems, and vehicle lighting.With a high effective duty ratio, a dc-dc boost converter may theoretically achieve a high step-up voltage.However, the influence of power switches and the equivalent series resistance(ESR) of inductors and capacitors limit the step-up voltage gain in practise.

When a high step-up voltage gain at a high duty ratio is required, the typical boost converter is turned to. However, the equivalent series resistance of inductors and capacitors, as well as the diode's reverse recovery difficulty, place constraints on the circuit's efficiency and voltage gain. Because of the transformer's leakage inductance, high voltage stress, and power waste caused by the converter's active switch. A resistor-capacitor-diode snubbed may be used to decrease the voltage stress on the active switch and so lessen the Voltage spike. However, doing so reduces efficiency. In order to reduce the input ripple current, converters based on the coupled inductor are created. These converters use an extra LC circuit with a connected inductor to achieve their low input current ripple.

Foundations of fuzzy logic

The quantity and diversity of fields where fuzzy logic has been used have grown substantially in recent years. Consumer electronics like cameras and camcorders are only the beginning; industrial process control and medical equipment are just a few examples of the more serious uses. You need to know what is meant by "fuzzy logic" before you can appreciate why its usage has increased.

One may use fuzzy logic in two distinct ways. As an extension of multivalve logic, fuzzy logic may be thought of as a logical system. A more general definition of fuzzy logic (FL) would include the theory of fuzzy sets, which deals with categories of things that have fuzzy bounds and where belonging is a question of degree rather than absolute truth. From this vantage point, a subset of FL is "fuzzy logic" in the restricted sense. Fuzzy logic is conceptually and practically distinct from more conventional multi-gate logical systems, even in its narrower definition.In every way, the fuzzy logic toolkit is superb. This boosts the utility of fuzzy logic as a method for developing smart systems. Fuzzy Logic Toolbox is simple to learn and implement. Last but not least, it gives an accessible and up-to-date overview of the approach of fuzzy logic and its many uses.

Fuzzy logic is predicated on the question, "How critical is it to be absolutely correct when an approximate answer will do?"

To apply fuzzy logic to a problem, you may utilise the Fuzzy Logic Toolbox add-on for MATLAB, a technical computer programme. Fuzzy logic is an interesting field of study because it effectively balances the need for accuracy with the value of significance, a task that humans have been juggling for a very long time. Although the discipline of fuzzy logic as a contemporary and rigorous science is relatively new, the notion of fuzzy logic itself depends on time-tested aspects of human thinking.

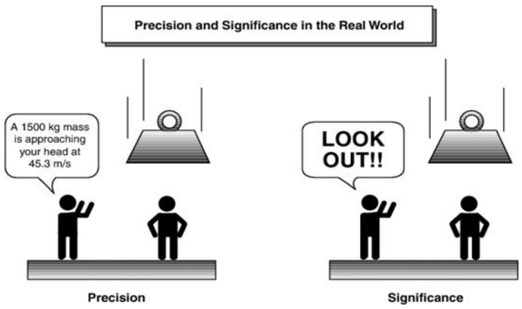

Fig.1: Fuzzy descriptions

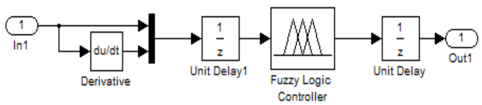

Fig.2: Fuzzy interference system

IV. PROPOSED SYSTEM AND CONTROL DESIGN

PROPOSED SRM

Fig. 1 depicts the 20 pole 30 slot SRM (model B) that fulfils the maximum rotation speed of 20000rpm, and Table I details the specifications of both this and the 8 pole 12 slot SRM (model A), which satisfies the maximum rotation speed of 50000rpm. Figure 1 and Table I demonstrate that in order to test the feasibility of control under high-speed rotation, a 20-pole 30-slot SRM was developed with the same electrical angular frequency and electrical properties as an 8-pole 12-slot SRM. Here is an expression for the electrical frequency at maximal rotation: Maximum electrical frequency fm, maximum rotation speed Nm, and pole count P equal to 60 m m P f N (1). According to the formula (1), the model A has a maximum electrical frequency of 6.67kHz. To ensure that model B has the same maximum electrical frequency as model A at the same maximum rotation speed of 20000rpm, the number of poles is set to 20. Their outside diameters, stack lengths, and air gap lengths are all identical among these two SRMs. In addition, as can be seen in Fig. 2, they are constructed with a nearly uniform distribution of self-inductance. This is how the torque of SRMs is written out: Output torque (T), inductance (L), electric angle (), and phase current (i) are represented by 2 2 P L T i (2). As demonstrated in (2), the output torque is proportional to the number of poles when supplied with a constant current value. This means that model B has a torque that is 2.5 times that of model A. However, in order to get the same torque, the current needed by Model B is 0.63 times that of Model A. The current-torque characteristics are shown in Fig. 3. Figure 3 demonstrates that in the no magnetic saturation region of low current, model B's torque is 2.5 times that of model A while using the same current.

CONTROLLABILITY OF VECTOR CONTROL FOR SRM

A. Vector control's foundational theory and the state of its controller

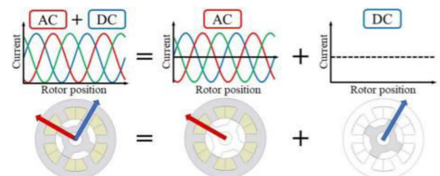

Fig. 4. Vector control of SRM.

The SRM vector control is shown in Fig. 3. The excitation current is a three-phase sinusoidal current with DC offset. The stator's magnetic field rotates because of the alternating current. The DC part generates a magnetic flux vector that rotates in response to the rotor's orientation. This vector of magnetic flux may be thought of as the magnetic flux in the rotor field. Because of this, torque is produced when the rotor's magnetic flux interacts with the stator's revolving magnetic field. The mathematical formula [9][10] describes the creation of torque during vector control of the SRM. Zero-phase and the d-q axis are used to represent the voltage equation of the equivalent SRM. where d-axis voltage (vd), q-axis voltage (vq), zero-phase voltage (v0), d-axis current (id), q-axis current (i0), winding resistance (R), DC component of self-inductance (Ldc), and self-inductance amplitude (Lac) are all variables.

The DC portion of the excitation current is used to derive the zero-phase portion, as indicated in (3). The virtual rotor flux is calculated using the second term in (3)'s inductance matrix, as shown below. Where r is the virtual rotor flux, we get 0 2 ac r L i (4). Thus, the zero-phase current is demonstrated to be the source of the virtual rotor flux in (4). Then, we can write down the SRM torque as: The zero-phase and q-axis currents are equal to the rotor flux and torque currents, as described by equations (4) and (5): 2 T P i r q (5) 0 2 T PL i i ac q (6). The SRM drive's vector control system, derived from Eqs. (4) and (5), is seen in Fig. 5.

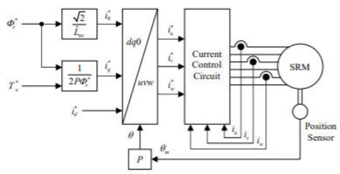

Fig. 5. Vector control system for SRM drive.

Fig. 4. Vector control system for SRM drive.

[13] explains the current controller that is being used. The present vector control controller is seen in Fig. 6. Figure 6 depicts the three components of the controller: the current PI controller, the decoupling controller, and the feedforward controller. A carrier-based PWM inverter may follow the voltage instructions from these controllers. Each axis and phase is individually controlled using a PI controller. Here is how the transfer function is written down: The transfer function, gain, and time constant of the PI controller are denoted by GPI, Kc, and c in the expression 1 () 1 PI c c G s K s (7). The controlled-SRM, thanks to the decoupling and feed-forward controllers, may be recognised as the RL circuits on the revolving reference frame. The time constant of the machine being controlled (Ldc/R) is chosen as the value of c to provide the desired current response at the first order. Kc, the gain, is tailored to the system's required reaction time. In this study, the controller utilised in simulations and experiments is the current controller.

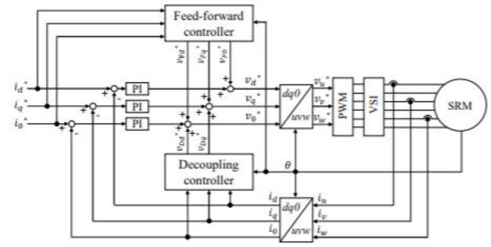

Fig. 5. The Vector Control System as it Exists Currently.

B. Controllability of high speed drive

When calculating the output power required and the rotation speed of 20000 rpm, the switching frequency and bus voltage are taken into account. Under the conditions of 20000 rpm rotation speed and 16.2 Nm reference torque, the simulation assesses the current waveform and the torque waveform for the switching frequency. Figure 7 depicts the switching frequency current and torque waveforms. Total harmonic distortion (THD) and current ripple ratio (CRR) are determined when the switching frequency is altered as follows (9): THD = CRR = I1 / THD. The actual values of the harmonic currents at each rank are given in. Maximum current amplitude (imax), lowest current amplitude (imin), and average current amplitude (iave) are denoted by imax, iimin, and iave, respectively. Increasing the switching frequency decreases the THD and the current ripple ratio. Since iron loss in a high-speed drive rises in response to harmonic fluxes, minimising THD is essential.

V. SIMULATION RESULTS

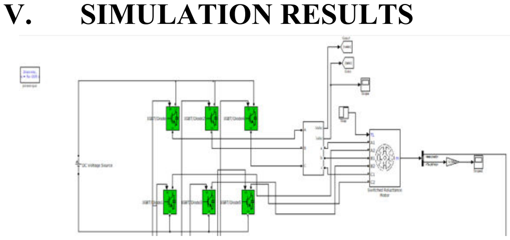

Fig6 : Proposed Simulation Diagram

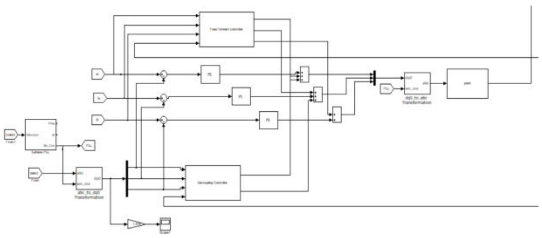
Fig7: Control Design

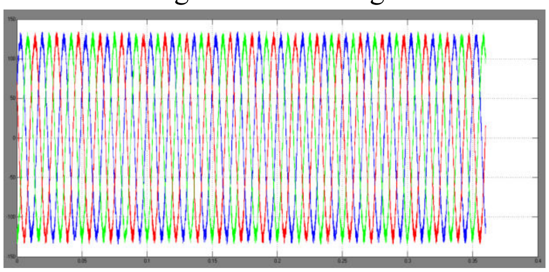
Fig8 : SRM Input Current

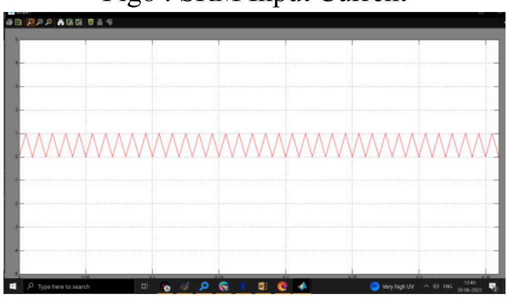
Fig9 : d-axis , q-axis, zero-phase current

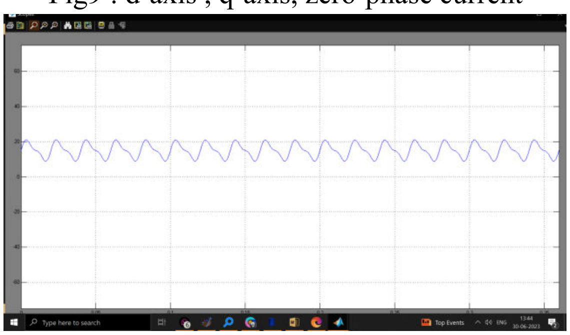
Fig10 : Torque

VI. CONCLUTION

The proposed Fuzzy Logic-Enhanced Vector Control scheme effectively addresses the control challenges associated with Switched Reluctance Motors in electric vehicle applications. By incorporating fuzzy logic into the vector control loop, the system adapts to variations in load and speed, delivering smoother torque and more accurate speed regulation. Simulation results validate the superior performance of the proposed method in terms of reduced torque ripple, improved dynamic response, and better energy efficiency compared to traditional controllers.

The study confirms that integrating intelligent control techniques with vector control enhances the practical usability of SRMs in high-performance EV drive systems. As future work, the implementation of the control system in real-time hardware and the inclusion of fault-tolerant features could further enhance the viability of SRMs as a mainstream solution in electric mobility.

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