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A new optimal space vector modulation with DTC switching strategy for induction motor control

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ABSTRACT

Efforts to achieve swift and precise dynamic torque control have been central in AC drive research. Recent advancements in embedded computer systems have highlighted direct torque control (DTC) and field-oriented control (FOC) as key methods for enhancing torque dynamics, both utilizing space vector modulation (SVM) to optimize voltage source inverter positioning. This study introduces a novel synthesis by integrating DTC with SVM to address limitations in conventional DTC, which suffers from limited voltage vector availability, leading to undesirable torque behavior and significant current fluctuations. The primary goal is to develop an optimal switching modulator for the fastest torque response through the combined application of DTC and SVM. The proposed strategy optimizes DC bus usage, reduces torque fluctuations, minimizes total harmonic distortion in AC motor current, decreases switching losses, and ensures seamless digital system integration. Simulations using MATLAB/Simulink demonstrate significant torque, current, and flux linkage ripple reductions, validating the approach's effectiveness. This integration overcomes established limitations, extending the capabilities of motor control methodologies and offering enhanced performance and operational integrity in induction motor drive systems.

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1. INTRODUCTION

Efforts to achieve swift and precise dynamic torque control have long been a central focus in AC drives research. In recent years, advancements in embedded computer systems have propelled two prominent methodologies, direct torque control (DTC) and field-oriented control (FOC), to the forefront as pivotal avenues for enhancing torque dynamics [1]. Both approaches utilize space vector modulation (SVM) to position the voltage source inverter within the overmodulation realm, aiming for optimal torque response. This study pioneers a novel synthesis by integrating DTC with SVM, addressing inherent limitations present in conventional DTC schemes. Traditional DTC, constrained by limited voltage vector availability to the motor, results in undesirable torque behaviors and pronounced current fluctuations [2]-[6]. In this paper, we propose the novel method of SVM with DTC is to formulate an optimal switching modulator designed to elicit the swiftest achievable torque response. This is achieved through the symbiotic application of DTC and SVM. A key strength of the proposed strategy lies in its ability to optimize DC bus usage, dampen torque fluctuations, attenuate total harmonic distortion in AC motor current, mitigate switching losses, and ensure seamless integration into digital systems. The SVM-DTC configuration is meticulously simulated using MATLAB/Simulink, demonstrating remarkable reductions in torque, current, and flux linkage ripple. This substantiates the effectiveness of the devised approach, positioning it as a significant stride toward achieving enhanced dynamic control in induction motor drive systems. By successfully overcoming established limitations [2]-[6], the fusion of DTC and SVM extends the frontiers of motor control methodologies, offering newfound potential for improved performance and operational integrity.

2. TORQUE CONTROL TECHNIQUES

The two dominant sensorless control methodologies for induction machines (IMs) are field-oriented control (FOC) and direct torque control (DTC). Both field-oriented control and direct torque control negate the necessity for coordinate transformations, pulse width modulation (PWM) signal generators, current controllers, or position encoders, which can introduce delays and mandate the utilization of mechanical transducers. Despite its simplicity, DTC offers swift, instantaneous torque control in both steady-state and transient operating conditions, in alignment with its fundamental control mechanism [7]. Given the imperative need for electric vehicle (EV) drive systems to exhibit rapid torque responses, cost-effectiveness, reliability, and robustness, DTC proves to be particularly advantageous for EV applications.

DTC's fundamental principle revolves around the direct selection of stator voltage vectors based on dynamic discrepancies, thereby avoiding the complexities of field-oriented control. The foundational work by Takahashi and Depenbrock introduced this methodology, involving the comparison of reference and actual torque along with stator flux linkage values [8]. By eliminating the requirement for intricate field orientation and inner current regulation loops, DTC achieves both rapid and precise torque responses, making it particularly suitable for saturated voltage operations.

Embracing this principle facilitates decoupled control over flux and torque without the necessity for coordinate transformations, PWM pulse generators, or other intricate control strategies. This approach involves employing two hysteresis controllers, depicted in Figure 1, to determine the motor's input voltage. These controllers select the appropriate voltage vectors from an inverter's lookup table, ensuring that stator flux and torque remain within the limits defined by two hysteresis bands, as shown in Figure 2 [9]. The associated switching table, illustrated in Table 1, dictates the voltage vector based on the stator flux position and the required variations in stator flux magnitude and torque [10]. The voltage source inverter (VSI) comprises two zero voltage vectors and six voltage vectors that are uniformly spaced and possess equal amplitudes. Figure 3 provides a visualization of the VSI's voltage vectors.

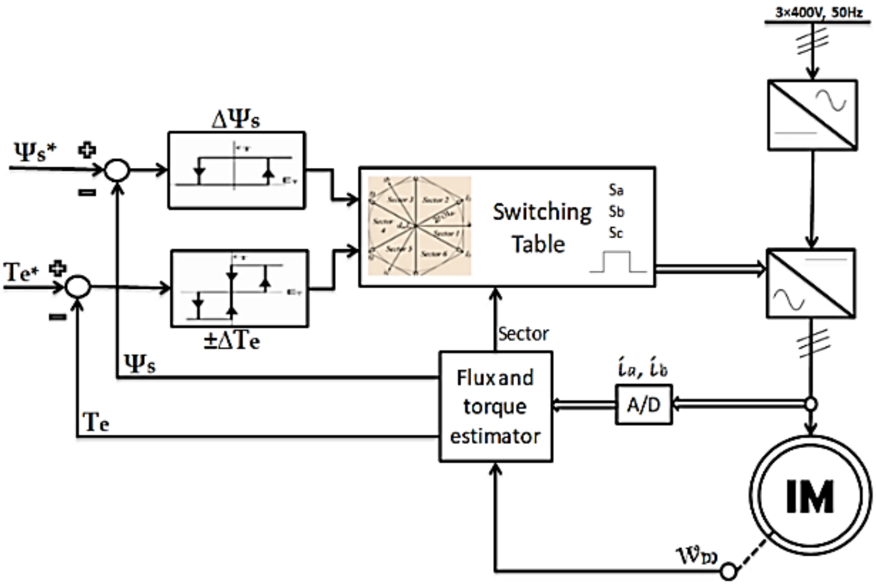

Figure 1. The block diagram of general DTC

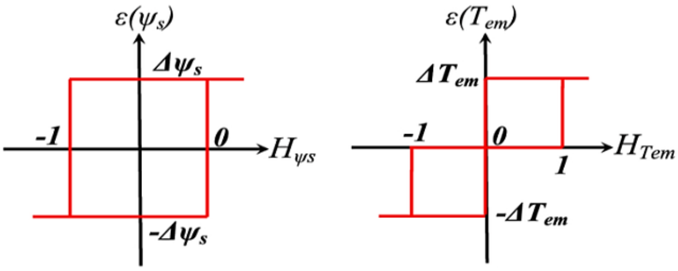

Figure 2. Hysteresis-based comparison: (a) stator flux and (b) torque

Table 1. Switching table

Flux error position	Torque error position	Sec I	Sec II	Sec III	Sec IV	Sec V	Sec VI
1	1	V2	V3	V4	V5	V6	V1
	0	V7	V0	V7	V0	V7	V0
	-1	V6	V1	V2	V3	V4	V5
0	1	V3	V4	V5	V6	V1	V2
	0	V0	V7	V0	V7	V0	V7
	-1	V5	V6	V1	V2	V3	V4

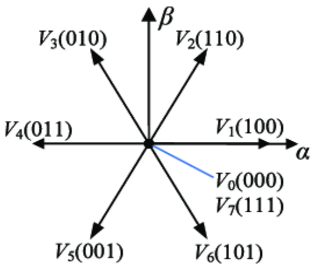

Figure 3. VSI voltage vectors

Despite its simplicity, direct torque control (DTC) faces several notable challenges. The basic DTC strategy utilizing hysteresis controllers exhibits several noteworthy drawbacks. These include fluctuations in inverter switching frequency, considerable torque fluctuations, and a resulting increased requirement for sampling to address digital implementation concerns [11]-[13].

$$V_{sd} = \frac{2}{3} V_{dc} \left(S_A - \frac{S_B + S_C}{2} \right) \tag{1}$$

$$V_{sq} = \frac{1}{\sqrt{3}} Vdc \left(S_A - S_C \right) \tag{2}$$

$$i_{sd} = i_{SA} \tag{3}$$

$$i_{sq} = \frac{i_{SA} + 2 i_{SB}}{\sqrt{3}} \tag{4}$$

$$|\psi_s| = \sqrt{\psi_{sd}^2 + \psi_{sq}^2} \tag{5}$$

$$T_e = \frac{3}{2} P(\psi_{sd} i_{sq} - \psi_{sq} i_{sq}) \tag{6}$$

$$\psi_{sd} = \int (V_{sd} - R_s i_{sd}) dt \tag{7}$$

$$\psi_{sq} = \int \left(V_{sq} - R_s i_{sq} \right) dt \tag{8}$$

3. PROPOSED DTC WITH SPACE VECTOR MODULATION SYSTEM

In this section, we will introduce the DTC-SVM methodology, which employs a closed-loop approach for torque control. The schematic representation of this configuration is illustrated in Figure 4. DTC involves the anticipation of the voltage required to achieve a predefined output torque, leveraging an induction motor model [14], [15]. Instantaneous stator flux and output torque can be ascertained using solely current and voltage information. Subsequently, the voltage essential to steer the flux and torque towards the desired levels within a specified timeframe is projected through the utilization of an induction motor model. The objective of the DTC-SVM approach, distinct from conventional DTC, centers on approximating a reference stator voltage vector V*S for the purpose of orchestrating the power gate operations of the inverter with consistent switching frequency. The inverter can now generate a voltage vector with varying direction and magnitude during each sampling interval. As a result, variations in stator flux deviations can manifest in diverse directions and magnitudes, leading to smoother alterations in torque. In the latter part of the 1980s, a team of German researchers introduced the concept of space vector modulation (SVM) for the first time. Since then, extensive investigations have been undertaken concerning the dq theory and the utilization of SVM methodologies. SVM techniques offer a spectrum of advantages, encompassing enhanced utilization of the DC bus, diminished torque fluctuations, reduced total harmonic distortion (THD) in the current of the AC motor, minimized switching losses, and seamless integration into digital systems. Within the framework of the direct torque control (DTC) paradigm, the SVM methodology is implemented within each cycle period to ascertain the requisite voltage space vector for precise recalibration of flux and torque discrepancies [16]. The integration of SVM with DTC has significantly curtailed torque ripple, maintaining a consistent switching frequency [17]-[19].

The computation of the stator flux vector, denoted as Ψ_s, and the resultant motor torque, T_em, can be accomplished using (9) and (10). These equations primarily rely on familiarity with the voltage vector previously employed, the computed stator current, and the stator resistance.

$$\Psi_s = (V_s - I_s R_s)\Delta t \tag{9}$$

$$T_{em} = \frac{3}{2}\frac{p}{2}(\Psi_s \times I_s) \tag{10}$$

Upon determining the magnitude of the current stator flux and the resulting torque, it becomes possible to calculate the necessary modification to attain the desired values by the end of the ongoing switching interval [20]-[23]. The voltage essential for nullifying torque and flux discrepancies is directly ascertained. This anticipated voltage is subsequently implemented, with the utilization of space vector modulation (SVM) to generate the voltage patterns. In cases where the inverter is unable to deliver the necessary voltage, the voltage vector that steers torque and flux closer to the desired level is chosen and maintained throughout the cycle duration [24], [25].

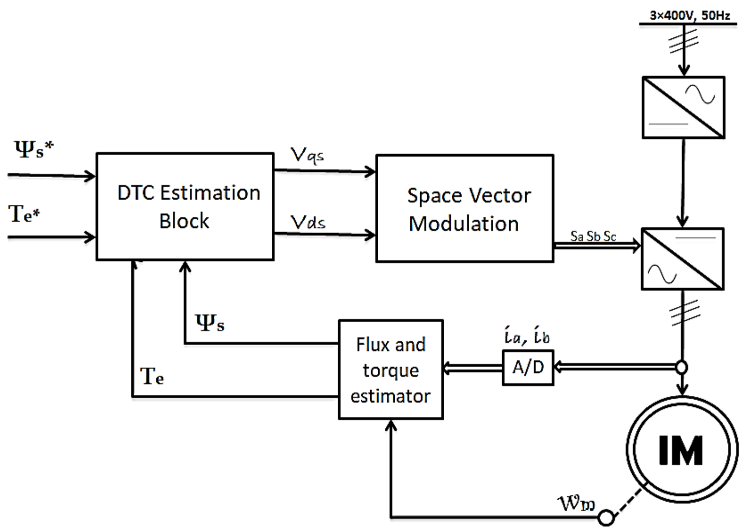

Figure 4. Proposed system block diagram (DTC-SVM)

The following equations can be used to compute the switching times.

$$V_s^* = V_{sd} + jV_{sq} \tag{11}$$

The values of Vsd and Vsq are obtained from the suitable voltage vectors corresponding to each sector:

$$T_Z V_s^* = T_A V_1 + T_B V_2 \tag{12}$$

$$T_A \sqrt{\frac{2}{3}} V_{dc} \begin{bmatrix} cos\ 0^o \\ \sin 0^o \end{bmatrix} + T_B \sqrt{\frac{2}{3}} V_{dc} \begin{bmatrix} \cos\left(\frac{\pi}{3}\right) \\ \sin\left(\frac{\pi}{3}\right) \end{bmatrix} \tag{13}$$

$$= T_Z \sqrt{\frac{2}{3}} V_{dc} a \begin{bmatrix} \cos\gamma \\ \sin\gamma \end{bmatrix} \tag{14}$$

$$T_A = T_Z a \frac{\sin\left(\frac{\pi}{3} - \gamma\right)}{\sin\left(\frac{\pi}{3}\right)} \tag{15}$$

$$T_B = T_z a \frac{sin\ (\gamma)}{\sin\left(\frac{\pi}{3}\right)} \tag{16}$$

$$T_0 = T_7 = T_z - T_A - T_B \tag{17}$$

during the time period $0 \leq \gamma \leq \frac{\pi}{3}$, where $a = \frac{|V_s^*|}{\sqrt{\frac{2}{3}} V_{dc}}$.

During the phase of steady-state operation, the reference vector, indicated as V*s and defined by an unchanging amplitude and frequency, is recorded at regular intervals of Tz. Within this defined sampling period, the inverter experiences transitions between different switching states, occupying them for varying spans of time. This controlled modulation guarantees that the mean space vector formulated over the course of the sampling interval aligns accurately with the sampled characteristics of the reference vector in regards to both magnitude and orientation [26]-[28].

The permissible array of switching states within Tz encompasses not only the two zero states but also the active states, SA and SB, orchestrated through vectors V1 and V2, serving to establish the bounds of the sector's initiation and conclusion, as visually depicted in Figure 5. Active switching states specifically denote the two modes, SA and SB, with SA representing inverter states (001), (100), or (010), and SB symbolizing inverter switching states (101), (110), or (010), (011). The time intervals attributed to active switching states, namely TA and TB, are defined as active vector periods. Additionally, the temporal spans linked to null switching states, S0 (000) and S7 (111), are denoted as null vector periods, T0 and T7. By integrating the space vector pulse width modulation (PWM) methodology within DTC, not only is the transient performance and robustness of DTC retained, but the amplitude fluctuations of the steady-state torque are also mitigated [29]. Furthermore, the inverter's continuous and fully adjustable switching frequency remains a prominent feature [30].

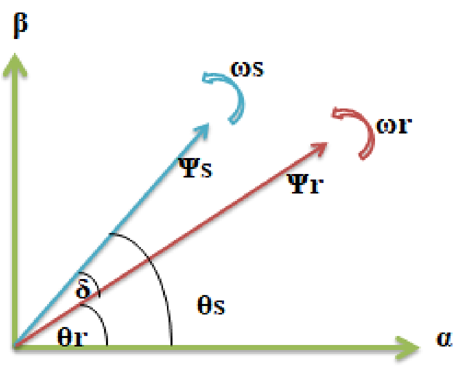

Figure 5. Boundaries of the sector

4. RESULTS AND DISCUSSION

The simulation segment encompasses the creation and assessment of the tailored direct torque control (DTC) methodologies. These methodologies were conceived and subsequently simulated using the MATLAB/Simulink environment, as depicted in Figure 6. To model the system, an induction motor is utilized, and its pertinent specifications are detailed in Table 2.

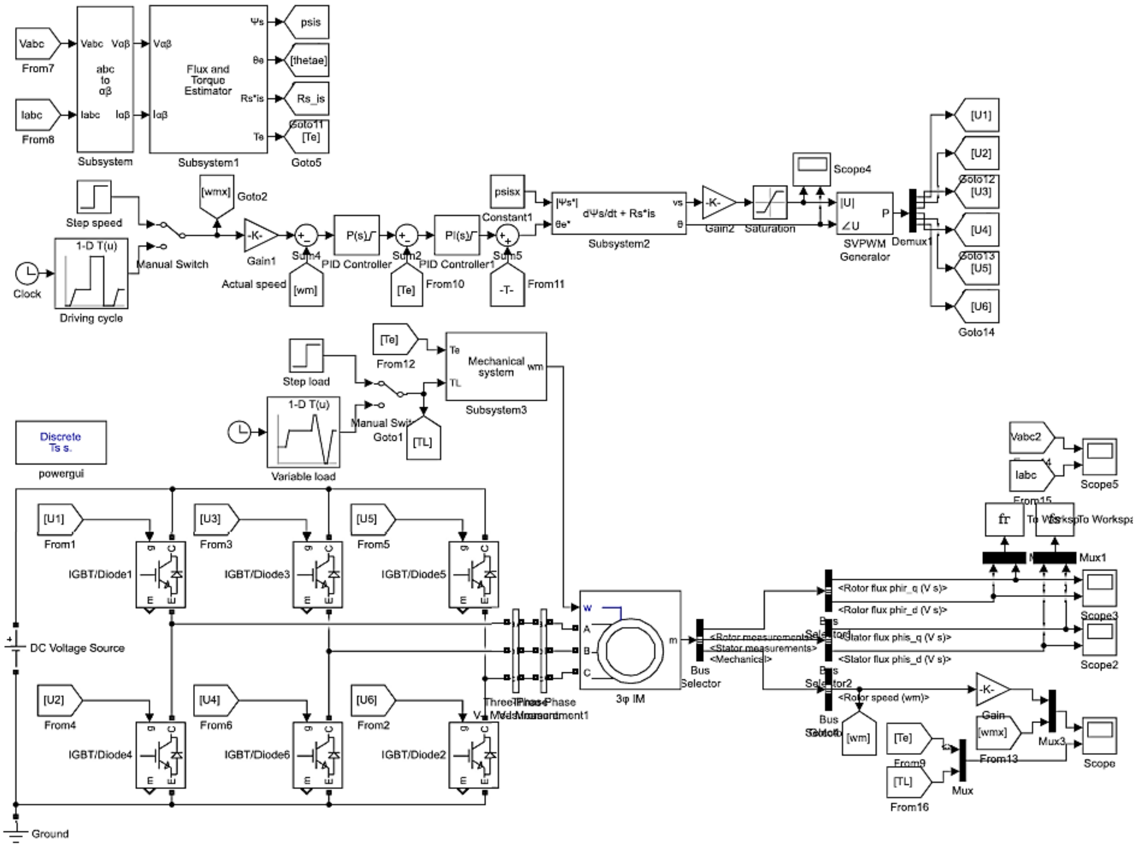

Figure 6. Simulation setup for SVM-DTC controlled induction motor system

Table 2. Technical specification of the induction motor

Parameter	Value
Stator resistance	$R_s = 1.405\ \Omega$
Rotor inductance	$L_r = 0.005839\ H$
Stator inductance	$L_s = 0.005839\ H$
Base speed	$N_b = 1430\ rpm$
Frequency	$f = 50\ Hz$
Rotor resistance	$R_r = 1.395\ \Omega$
Mutual inductance	$M = 0.1722\ H$
Phase voltage	$V = 240\ V$
Inertia	$J = 0.003\ kgm^2$

4.1. Simulation setup and motor model

Exploring the intricacies of advanced direct torque control (DTC) strategies necessitated the development of a robust simulation framework, meticulously crafted within the versatile MATLAB/Simulink software. This platform served as the testing ground where innovative adjustments to the conventional DTC approach were seamlessly incorporated. Through a series of methodical simulations, the repercussions and efficiencies of these proposed modifications were thoroughly scrutinized, shedding light on their potential advantages and drawbacks within the dynamic context of motor control systems.

4.2. Motor selection and data incorporation

For the purpose of system modeling, an asynchronous motor was selected as the core component. The inherent characteristics and parameters of this motor, crucial for accurate simulation, were extracted from pertinent datasheets. These specifications, providing a solid foundation for the model, are comprehensively outlined in Table 1.

4.3. DTC scheme design and implementation

To enhance the performance of direct torque control (DTC), innovative schemes were meticulously formulated with the specific aim of refining and optimizing its operational efficiency. These novel strategies, carefully designed to meet predefined objectives, were subsequently translated into functional Simulink blocks. This transformation facilitated the seamless integration of the conceptual enhancements into the simulation environment, allowing for a real-time assessment of their impact on the asynchronous motor.

4.4. Simulation architecture and evaluation

The MATLAB/Simulink platform facilitated the construction of a dynamic simulation architecture. This architecture intricately integrated the modified DTC strategies with the asynchronous motor model. The resultant simulations enabled the systematic observation and analysis of the motor's behavior under various operational conditions. By establishing this robust simulation setup and accurately incorporating motor specifications, the simulation section of this study lays the foundation for comprehensive insights into the performance enhancements offered by the proposed DTC schemes.

Figures 7 to 11 illustrate the steady-state performance of an induction motor under SVM-DTC. In Figure 7, we observe the pulse sequences for switches S1-S6, obtained via space vector PWM technique. Notably, S1's pulses are complementary to those of S4, as are S2's to S5's, and S3's to S6's. This symmetry in pulse behavior contributes to coordinated switch operation within the SVM-DTC strategy. The obtained simulation results hold pivotal implications in showcasing the efficacy of the proposed direct torque control (DTC) approach integrated with space vector modulation, especially in comparison to prior methodologies. This section provides a comprehensive analysis of each figure's outcomes, along with a succinct comparison highlighting the significance of the present work.

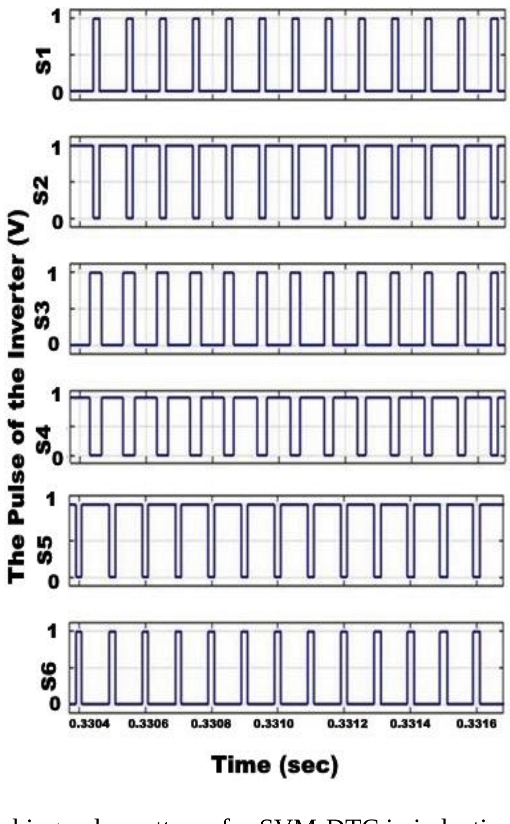

Figure 7. Switching pulse patterns for SVM-DTC in induction motor control

4.4.1. Stator flux dynamics

In Figure 8, the stator flux behavior is unveiled. This figure provides a clear visualization of how the proposed DTC with space vector modulation influences the stator flux, accentuating the precise control achieved under dynamic conditions. Comparing these results to previous approaches underscores the advancements in achieving optimized stator flux regulation, thereby enhancing overall motor performance.

4.4.2. Rotor flux variation

The rotor flux trends are depicted in Figure 9. This figure unveils the rotor flux's behavior within the proposed DTC framework, underscoring the robustness and accuracy of the approach in maintaining desired flux levels. By contrasting these outcomes with those of earlier methods, the progress achieved becomes evident, solidifying the claim that the proposed DTC with space vector modulation yields improved rotor flux dynamics.

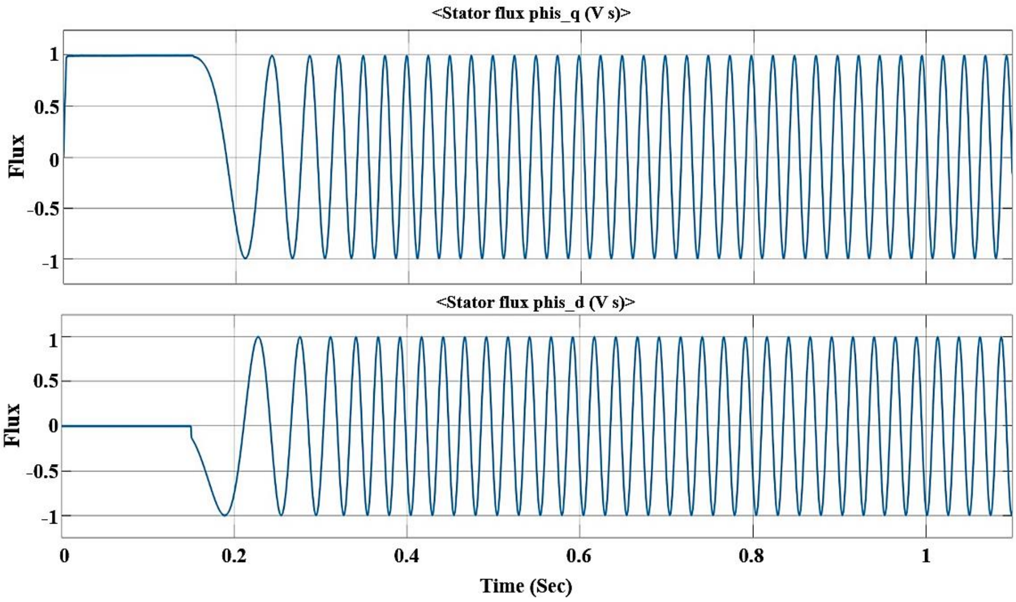

Figure 8. Stator flux dynamics in proposed SVM-DTC induction motor system

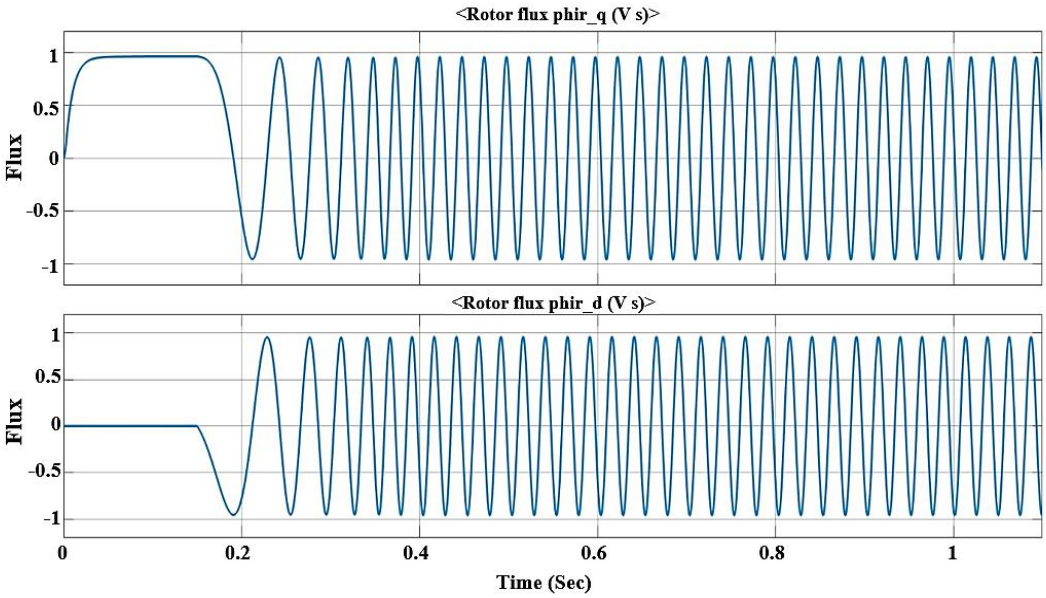

Figure 9. Rotor flux variation in SVM-DTC controlled induction motor system

4.4.3. Line voltage and current

Figure 10 presents a dual depiction of line voltage and current profiles. The upper portion illustrates voltage behavior, while the lower portion showcases current trends. This combined view provides a comprehensive insight into the interaction between voltage and current under the proposed approach. The juxtaposition of these aspects emphasizes the seamless integration achieved in the DTC system. This advancement, compared to preceding work, exemplifies the achievement of enhanced voltage and current control synchronization, a crucial achievement for motor stability.

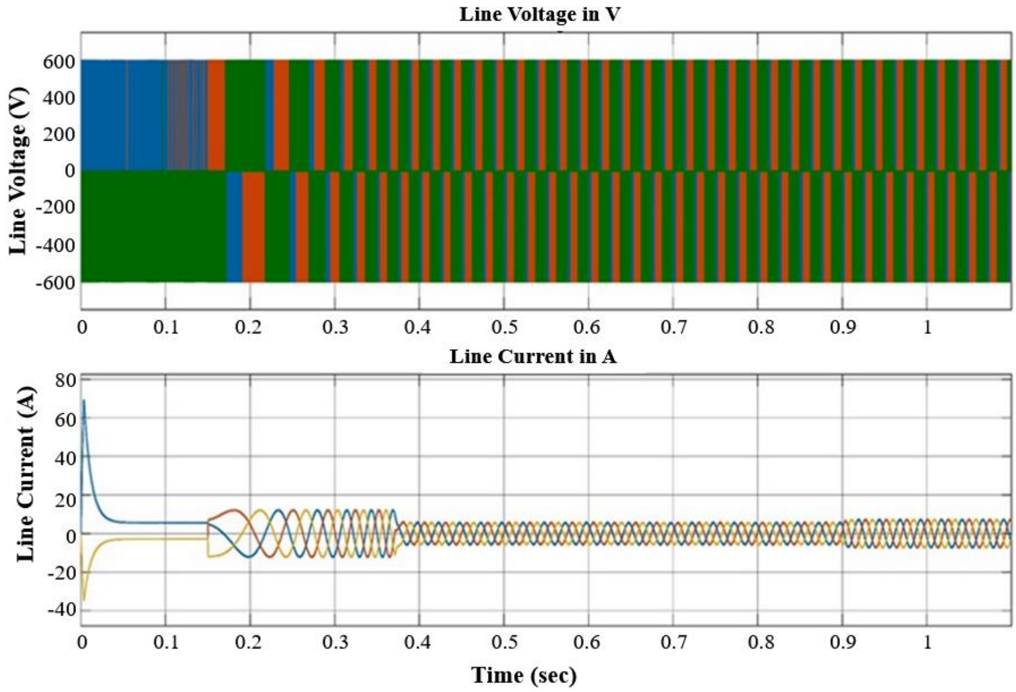

Figure 10. Line voltage and current behavior in SVM-DTC induction motor control

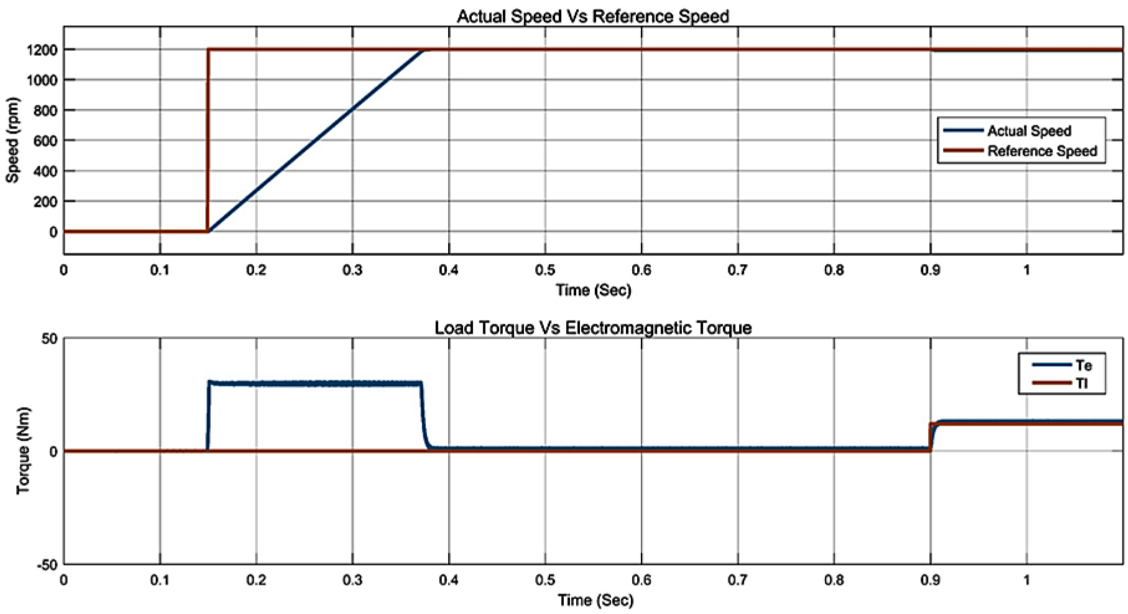

Figure 11. Speed and torque profiles in proposed SVM-DTC induction motor system

4.4.4. Speed and torque dynamics

In Figure 11, the speed and torque variations are portrayed. This tandem visualization accentuates the agility and precision of the proposed DTC methodology. The upper segment portrays speed, while the lower segment exhibits torque dynamics. A comparative analysis with prior research reveals that the proposed DTC with space vector modulation not only maintains speed stability but also exhibits superior torque response, significantly improving transient motor performance.

4.4.5. Comparative significance: enhancements and insights

The pivotal significance of this study lies in its ability to improve upon conventional DTC strategies. By integrating space vector modulation, the proposed methodology demonstrates improved control precision in stator and rotor flux, enhanced synchronization between voltage and current, and optimized speed and torque response. This advancement signifies a marked leap from previous work, offering a more effective, accurate, and stable control approach for induction motor operations. The proposed approach's ability to address and improve upon key motor control aspects accentuates its relevance and applicability within the realm of motor drive systems.

5. CONCLUSION

The integration of space vector modulation (SVM) within the direct torque control (DTC) framework has effectively addressed significant shortcomings, notably the pronounced flux and torque ripples. This innovative amalgamation has yielded substantial improvements in dynamic control across diverse operational scenarios, encompassing load variations, speed reversals, and low-speed operation. The successful reduction in torque ripple achieved through SVM-DTC, while simultaneously preserving a consistent switching frequency, underscores the method's competence. The validation of these advancements was conducted through comprehensive simulations utilizing MATLAB/Simulink. The outcomes substantiate the superiority of the proposed DTC scheme compared to existing counterparts. The amassed evidence points to a notable enhancement in the performance of the induction motor (IM) drive. The salient improvements encompass not only refined torque control and minimized flux ripple but also the overall robustness and operational integrity of the system. In summation, the outcomes affirm that the proposed DTC approach is highly compatible with IM drive operations. By effectively circumventing historical limitations and fostering enhanced performance attributes, the SVM-DTC method emerges as a noteworthy contribution to the realm of motor drive systems. The results obtained through simulations and subsequent analyses firmly support the conclusion that the proposed approach stands as a commendable solution for the efficient and optimized operation of IM drives.

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