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Control of Energy and Torque for Switched Reluctance Machine by DFEC

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Abstract

The following research deals with the control and optimization of the efficiency of Switched Reluctance Machines (SRMs) with a new method proposed for control. The new method proposed in this study, Direct Force and Energy Control DEFC, is based on Direct Torque Control (DTC). H. This control directly controls energy and force at the same time. The purpose of this control is to increase the efficiency of the SR motor and reduce motor torque ripple and vibration. In this study, we applied three control methods including the proposed method and the proposed method to control a switched reluctance motor. To prove the efficiency of DEFC, we compare our simulation results with those of his DEC, DFC, and traditional his DTC strategy. From the results, it was concluded that the proposed DEFC technique performed better than other methods, reducing the torque ripple to 10% and improving the performance of SRM.

Keywords: DEFC; DEC; DFC; DTC; SRM; torque ripple; Trf

Introduction

Over the past decade, researchers have put a lot of effort into studying Switched Reluctance Motors (SRMs) because they have many advantages, including: B. Simple structure, wide speed range, high starting torque, flexible control with fault tolerance, low inertia, high efficiency. SRM has applications in various fields such as hybrid electric vehicles, aviation industry, and consumer electronics. Advances in power converter and control technology have significantly improved the performance of SRMs. However, the dual nature of switching power supplies and SRMs makes them susceptible to various problems such as nonlinear magnetic characteristics, unwanted torque fluctuations, and acoustic noise. These issues can negatively impact system reliability and security. Furthermore, traditional tuning methods may not be able to precisely control SRMs, so innovative control and design strategies must be used to improve their performance. Therefore, researchers are focusing on finding creative approaches to improve the performance of SRM, such as using advanced control techniques and optimized designs. These efforts have significantly improved the performance and reliability of SRM, making it an attractive option for a variety of applications. However, to take full advantage of SRM, it is important to establish an effective control method that allows precise control of motor torque and speed. There are various ways to control SRM, each with its own advantages and disadvantages [1]. This article describes the work of various researchers in the field of switching reluctance motor control. Over the years, several studies have been carried out to develop advanced control methods for SRM. A study proposed by Hofmann and De Doncker in 2014 is Direct Instantaneous Force Control (DIFC) to address the acoustic noise problem of SRM. They proposed using a hysteresis-based DIFC controller instead of a PWM-based one to overcome the problem of large modulation-related harmonics in the spectrum [2]. The proposed control system was designed and evaluated through simulation and found to remove modulation-related harmonics from the audible spectrum while maintaining the same acoustic performance. Additionally, the switching frequency needs to be lower, which increases the efficiency

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of the inverter. In another study, the same last method is proposed, but using hysteresis-based his DIFC, these harmonics can be reduced while improving inverter efficiency. Waves can be removed. Additionally, the author presents a technique to minimize vibration mode 0, a common noise source in large his SRMs, by controlling the radial force of each phase to achieve an overall uniform radial force. I would like to suggest. Comparing this method with conventional techniques, we found that it is effective in reducing mode 0 excitation while potentially allowing coexistence of smooth force and torque control [3].

Direct Flow and Torque Technique (DFTC) is another common method that has been widely studied for SRM. A study by Shah et al. 2019 proposed an innovative Direct Torque Control (DTC) system to reduce the output torque variation of an SR motor by changing the sector boundaries and selecting the optimal voltage vector. I am. This technique keeps the stator flux constant and less sensitive to operating conditions, resulting in faster phase turn-off, higher torque/amplifier ratio, and less torque ripple compared to standard His DFTC. It will be lower. According to a study by a DITC method exists that addresses the high torque ripple and low efficiency of classical DITC by using an adaptive turn-on angle Torque Sharing (TSF) feature. This technique divides the work cycle into six sectors. It obtains candidate voltage states for each sector and adaptively updates the TSF curve and DITC sector placement based on changes in speed and load torque. This new DITC approach can reduce torque fluctuations and improve efficiency by adjusting the switch-on angle to speed and load torque variations. According to the modeling results, this approach can also improve the performance and start-to-run efficiency of his SRM. Another study by DFTC focused on Switching Reluctance Motors (SRMs) to optimize torque control settings, reduce vibration by reducing radial force dispersion, and minimize torque fluctuations. control strategy [4]. This strategy involves changing the control parameters offline and using Direct Force Control (DFC) to reduce the overall radial force variation. To compensate for torque ripple and vibration, a reference current adapter based on limiting torque and radial force fluctuations was developed. The reference current of the reference current adapter is automatically adjusted to balance torque ripple and vibration. The DFC controls the converter switch based on direct instantaneous torque management to achieve uniform overall radial force. In the study by a modified Torque Distribution Function (TSF) was proposed to reduce the torque ripple of Switching Reluctance Motor (SRM) over a wide speed range. TSF distributes torque between phases and reduces ripple caused by commutation [5]. However, as speed increases, the phase currents can no longer match the reference currents exactly, resulting in torque ripple. The authors suggest changing the TSF structure or current compensation to eliminate torque fluctuations over a wider speed range by extending the TSF operating range from the first to the second quadrant. Direct Energy Control (DEC), a study proposed by reduces the torque ripple and DC-link voltage ripple of SR motor drive system by controlling the magnetic field based on Direct Torque Control (DTC) technology. Reduce. The DEC solution simultaneously controls magnetically stored energy and instantaneous torque and, according to the authors' modeling results, can reduce DC link voltage ripple by almost half that of conventional techniques. The same author suggests using PDIEC to reduce torque ripple with his DC link capacitor in his SRM drive system. This method controls the energy flow in the DC link to produce a constant output torque and eliminates low-frequency fluctuations in the input energy by controlling both the stored field energy and the instantaneous torque simultaneously. . The proposed control based on direct torque control to remove torque fluctuation proposed in this study proves the effectiveness of the proposed control. In this study, we propose a new control method for Switched Reluctance Motors (SRM) called Direct Energy and Force Control (DEFC). Unlike traditional control methods such as Direct Torque Control (DTC), Direct Force Control (DFC), and Direct Energy Control (DEC), DEFC directly regulates force and energy rather than torque or flow. The purpose of our study is to investigate the influence of his DEFC on torque ripple and SRM effectiveness. To accomplish this, we compared the results of DEFC with those of DTC, DFC, and DEC. Our simulation results demonstrate the effectiveness of his DEFC in improving SRM efficiency and torque quality, which is a novel contribution of this study. Therefore, we conclude that the proposed DEFC technique is a promising solution to control his SRM and can significantly improve the performance. Below is a list of the main contributions of this article: 1. In this part, we model the proposed new Direct Energy And Force Control (DEFC) controller, explain how this controller method works, discuss the control vector selection, and present the simulation results of the controller. and its impact. Controlled by torque ripple. 2. The simulation results of the proposed controller were compared with the different methods considered in this study and the impact of the methods on torque ripple and motor SRM effectiveness.

Structure of Proposed System

Our approach to analysis will involve a detailed examination of each component of the system individually. This will enable us to gain a deeper understanding of the performance of the system and identify any areas that require improvement.

Design of SRM

The Switch Reluctance Motor (SRM) is a type of electric motor that uses magnetic reluctance. Both the rotor and stator have multiple poles which impact the rotor movement. The rotor moves to the position with the greatest winding inductance, controlled by the current commutation sequence through the stator windings. The performance and efficiency of the SRM depend on the control system's characteristics, such as turn-on angle, rotor direction, and current reference, which can be adjusted for optimal performance. Equation (1) describes the relationship between flux and reluctance and is crucial in understanding how magnetic fields interact and produce rotor movement. Optimal balance between flux and reluctance can improve SRM performance and efficiency.

$$\varnothing = \oint_{\wedge} Adl \qquad (1)$$

When the phases of the motor are completely separated from each other, the induced stream relationship simply depends on the excitation of the current and flux inductance. Flux-inductance describes the resistance of the magnetic track when the rotor moves from an unaligned to an aligned position. **FIG. 1(a) and FIG. 1(b)** show two conventional SRM flux distributions (at ϴ=0° and ϴ=45°) with the rotor axis completely aligned and unaligned with the stator poles. The magnetic field information over the entire cross- section is easily identified by inspecting the flux distribution plots, allowing for easy determination of local saturation and magnetic force distribution in relation to SRM terminal properties **FIG. 2**.

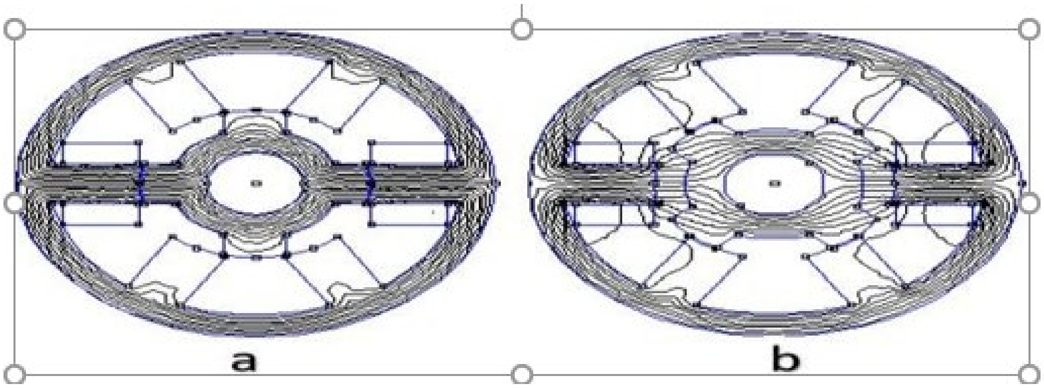

FIG. 1. **Two different flux diffusion of SRM**

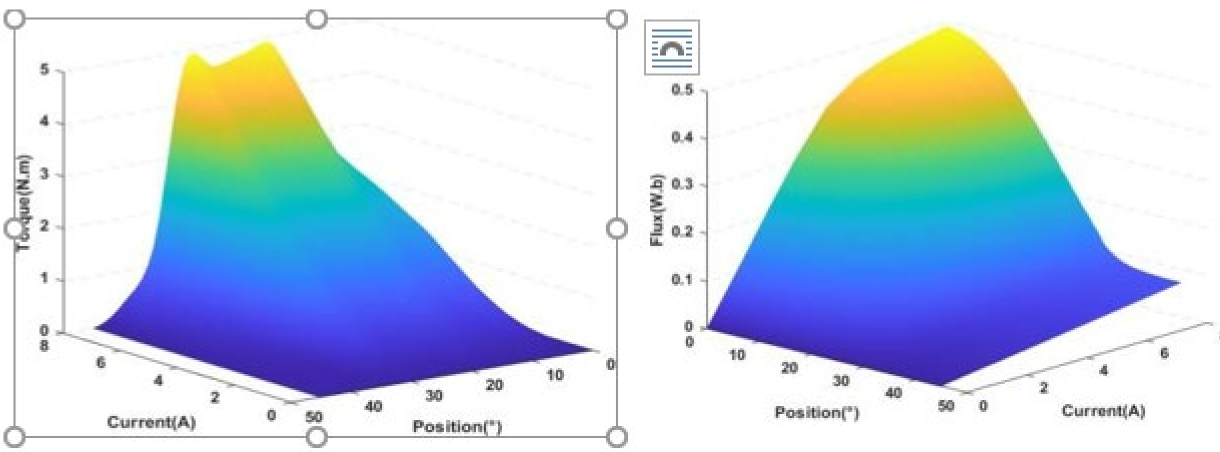

FIG. 2. **The torque and flux with deference position**

Furthermore, equation (1) can then be rewritten as follows:

Proposed method of control

To determine the efficiency of the proposed SRM control method, we conducted a comparative analysis with other existing control methods. Specifically, we applied several established control methods to the SRM system and compared the simulation results with those of the proposed method. The aim of this approach was to evaluate the performance of each control method and identify areas where the proposed method outperforms other control methods. By comparing the simulation results, we were able to quantify the effectiveness of the proposed method and demonstrate its superiority over other control methods. Overall, this approach allowed us to demonstrate the efficiency of the proposed SRM control method through rigorous and systematic comparisons with existing methods. We disclose direct control of torque and flux of a switched reluctance motor. This approach significantly reduces torque ripple and significantly improves performance. This form of command is based on directly determining the command sequence to be applied to the switches of the half-bridge converter. This decision is often based on the use of hysteresis controllers whose purpose is to adjust the state of the system, i.e. the amplitude of the stator flux and electromagnetic torque. The purpose of the control is to allow direct force control to follow a specified reference path. The goal of DFC is to adjust the converter switch so that the sum of the radial forces Fs generated in each phase of the stator reaches the desired value Fref at any time and maintains a maximum constant value to avoid mechanical disturbances. is to provide seamless total radial force. excitement. To bridge the gap between the required total radial force Fref and the actual total phase radial force Fs, the DFC block generates a converter switching signal. The asymmetric half-bridge topology allows the converter used to supply three alternative terminal voltages to the coupled phase windings. It reveals how to directly control the power and torque of an SR motor. This strategy significantly reduces torque fluctuations and significantly improves performance. This command version is based on directly determining the command sequence applied to the half-bridge converter switch. This choice usually relies on the use of a hysteresis controller, which has the ability to control the state of the system, i.e. to determine the energy and the amplitude of the electromagnetic torque. A comprehensive analysis of previous research on Switched Reluctance Motors (SRMs) has identified several areas where the current control methods used in these motors could be improved. To increase the efficiency of SRM, we proposed a new control method based on direct control of energy and force. In this paper, we propose a new control method for SR motors based on direct torque control to reduce torque ripple. H. Direct control over force and energy. The goal of Direct Energy and Force Control (DFEC), a technology based on direct torque control, is to control the converter switches such that the total radial force and the force generated in the stator stage becomes energy, and the radial It is to equalize the total force and energy in the direction. You can balance it and increase Fref and Wref to your desired values. The DFEC controller generates the power converter switching signals to reduce dF and dW. dF and dW are defined as the difference between the desired radial force Fref and the actual sum of the radial forces F for each phase and the sum of the desired radial energy Wref and the actual sum. Each radial energy W, phase. Against this background, direct force and energy controllers represent a new method for calculating the digital control signals applied to SRM converters. DFEC consists of two hysteresis controllers for force and energy. The first consists of two hysteresis controller units for force, and the other consists of two hysteresis controller units for force. It consists of an energy hysteresis controller, which generates the switching signals for each phase of the SRM. An illustration of the DEFC command is shown in Figure 3. Measuring the stator size can be used to estimate the energy (current and flux) **FIG. 3 and FIG. 4**.

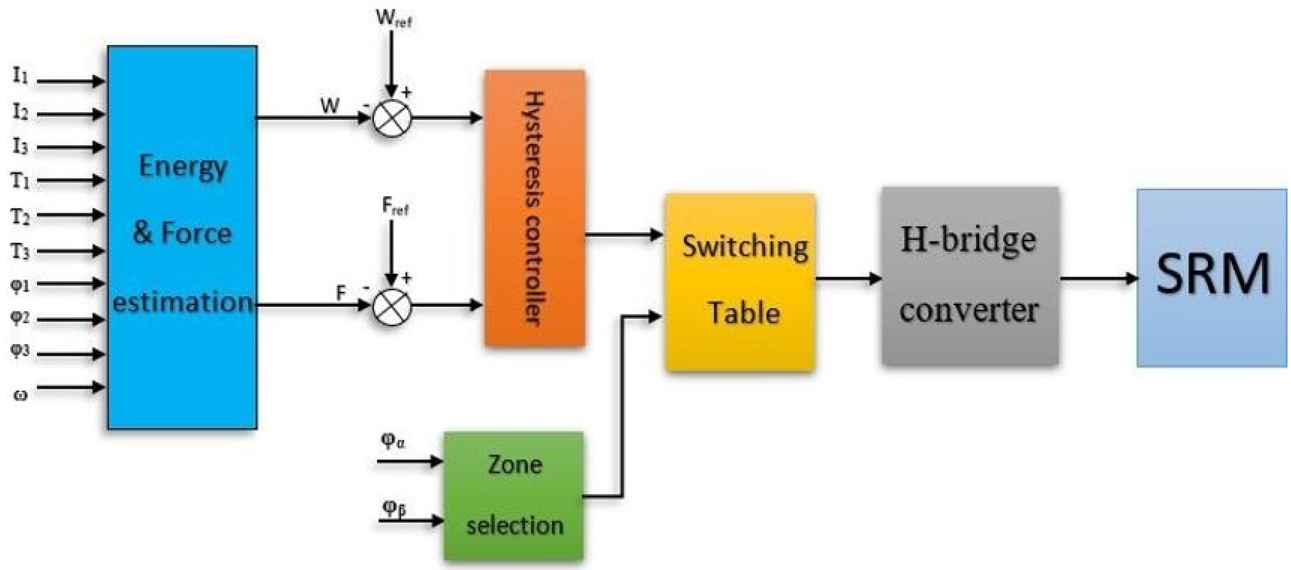

FIG. 3**. Schematic for direct force and energy control DEFC**

he energy is represented by the following equation.

$$\overline{W}\ (\theta,i)=L(\theta)i$$

$$\overline{W}\ (\theta,i)=\frac{1}{2}iT(\theta,i)$$

the force is determined by the following equations:

$$Ce\left(\theta,i\right)=\frac{1}{2}\frac{F^{(\theta,i)}*}{\omega}i(\theta)$$

$$F\left(\theta,i\right)=\frac{2*Ce(\theta,1)*\omega}{i\left(\theta\right)}$$

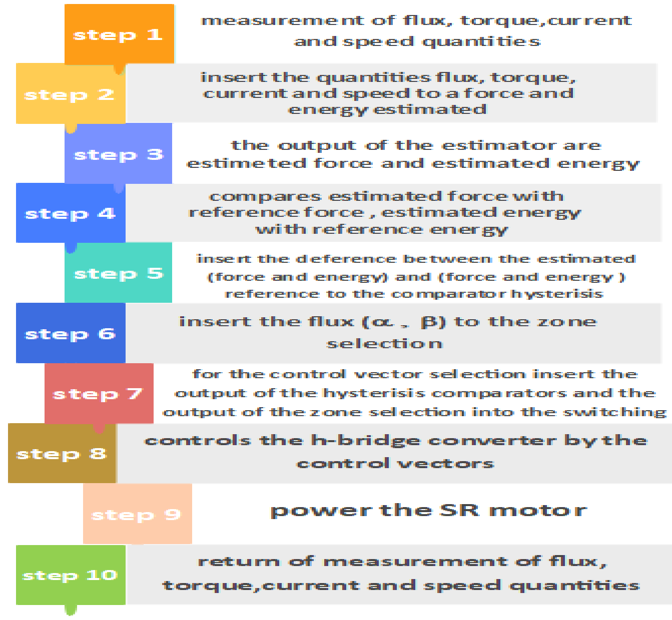

FIG. 4. **Organizational chart of the direct force and energy control DEFC**

In SRM, the asymmetric half-bridge circuit is typically used as the power of the converter to achieve simple control and phase independence. In order to choose the appropriate voltage vector, the output of the corrector must specify the energy module's development direction. A straightforward two-level hysteresis corrector is ideal for this and enables extremely good dynamic performance. The corrector's output, which is a Boolean variable, directly shows whether the co-amplitude energy has to be raised (1) or lowered (0). It has been feasible to control the motor SR in both directions of rotation by using a three-level hysteresis corrector. Indicated via a Boolean variable, the corrector's output shows whether the force's amplitude should be increased in absolute value (1) for a positive set point and decreased in absolute value (-1) for a negative set point (0). the following table represents the voltage vector choices and the control sector.

the goal of the corrector of energy is to maintain vector W's extremityin a rounded crown. In order to choose the appropriate voltage vector, the corrector's output must specify the direction in which the modulus of W is evolving. A straightforward two-level hysteresis corrector is ideal for this and enables very good dynamic performance. The corrector's output, which is a Boolean variable, directly indicates whether the amplitude energy has to be increased (1) or decreased (0) **FIG. 5 TABLE 1**.

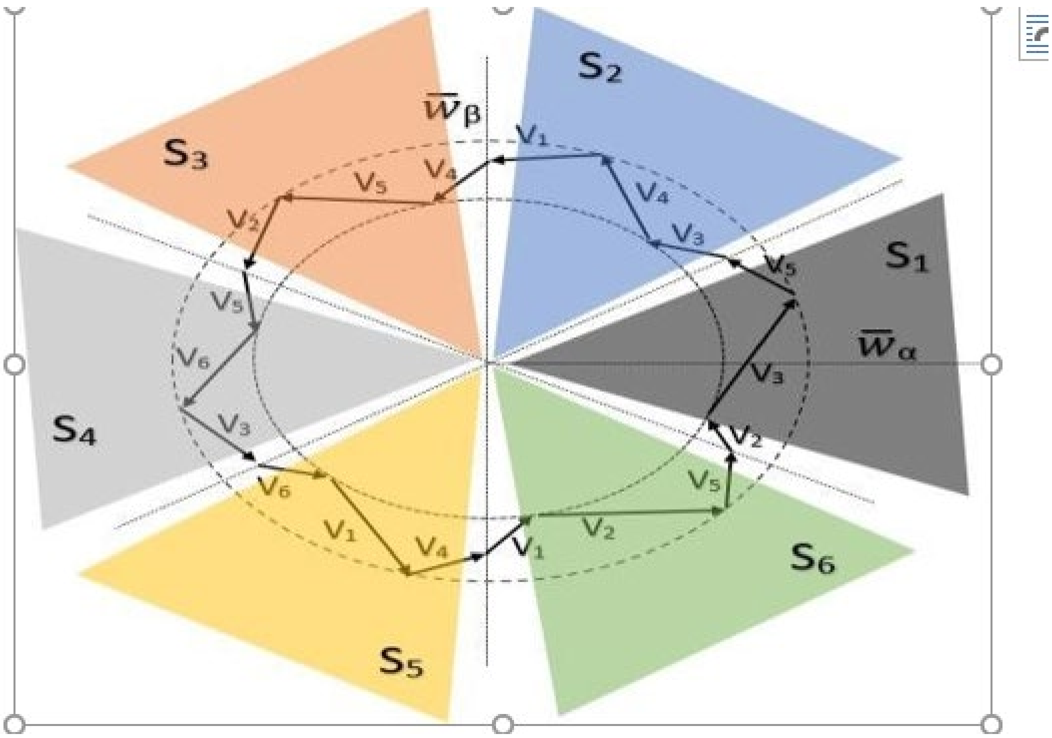

FIG. 5. **Organizational chart of the direct force and energy control DEFC**

TABLE. 1**. Selection of vectors of control**

section	dF=1, dW=1	dF=1, dW=0	dF=0, dW=1	dF=0, dW=0	dF=-1, dW=1	dF=-1, dW=0
S1	V2	V3	V7	V0	V6	V5
S2	V3	V4	V0	V7	V1	V6
S3	V4	V5	V7	V0	V2	V1
S4	V5	V6	V0	V7	V3	V2
S5	V6	V1	V7	V0	V4	V3
S6	V1	V2	V0	V7	V5	V4

Simulation result

In this section, the simulation results of four methods of control DTC, DEC, DFC and the proposed method DEFC and we show the torque in phases, total torque, current, flux and speed, the SRM work at a speed of 1600r/m for each method. for DTC the total torque is 5n.m when adding the load to the SRM the torque changes to 9n.m, the current suddenly changed from 16A to 24A, and the flux changes between 0.39Wb and 0.42Wb, the speed tracks the reference speed even when adding the load but the response of speed is slow to reach the reference speed and the torque ripple is large. for DEC before adding the load, the current is 10A and the flux is 0.42Wb after adding the load the current and flux changed to 21A and 0.45Wb the total torque suddenly changed from 4.5N.m to 6.2N.m, and the speed tracks the reference speed even when adding the load, the response of speed is a little quick but isn't the best to reach the reference speed and the torque ripple is small for the last method. For DFC the total torque is 5n.m when adding the load to the SRM the torque changes to 9n.m, the current changed from 16A to 24A, and the flux changes between 0.39Wb and 0.42Wb, the speed tracks the reference speed even when adding the load and , the response of speed is a little quick but isn't the best to reach the reference speed and the torque ripple is small for the DTC and almost the same result with DEC. in the proposed method DEFC we observe the total torque is 4.7n.m, when adding the load to the SRM the torque changes to 8.4n.m, the current changed from 10A to 20A, and the flux changes between 0.39Wb and 0.42Wb. the speed tracks the reference speed even when adding the load and the response of speed is fast and it is the best response in between the last methods to reach the reference speed, the SRM produced a small ripple torque compared us the last methods **FIG. 6 and FIG. 7**.

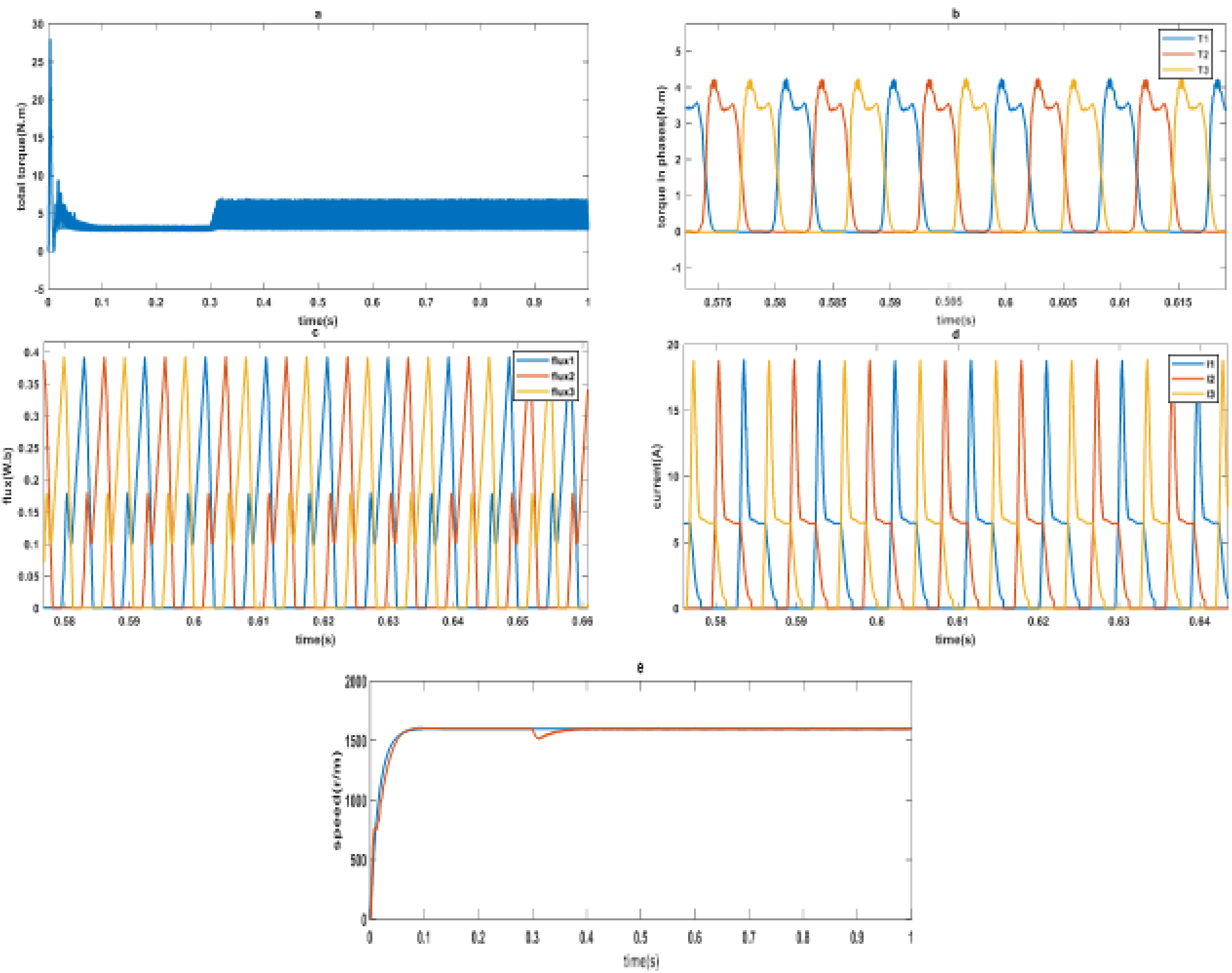

FIG. 6. Simulation result of DTC (a: total torque, b: torque in phases, c: flux, d: current, e:speed)

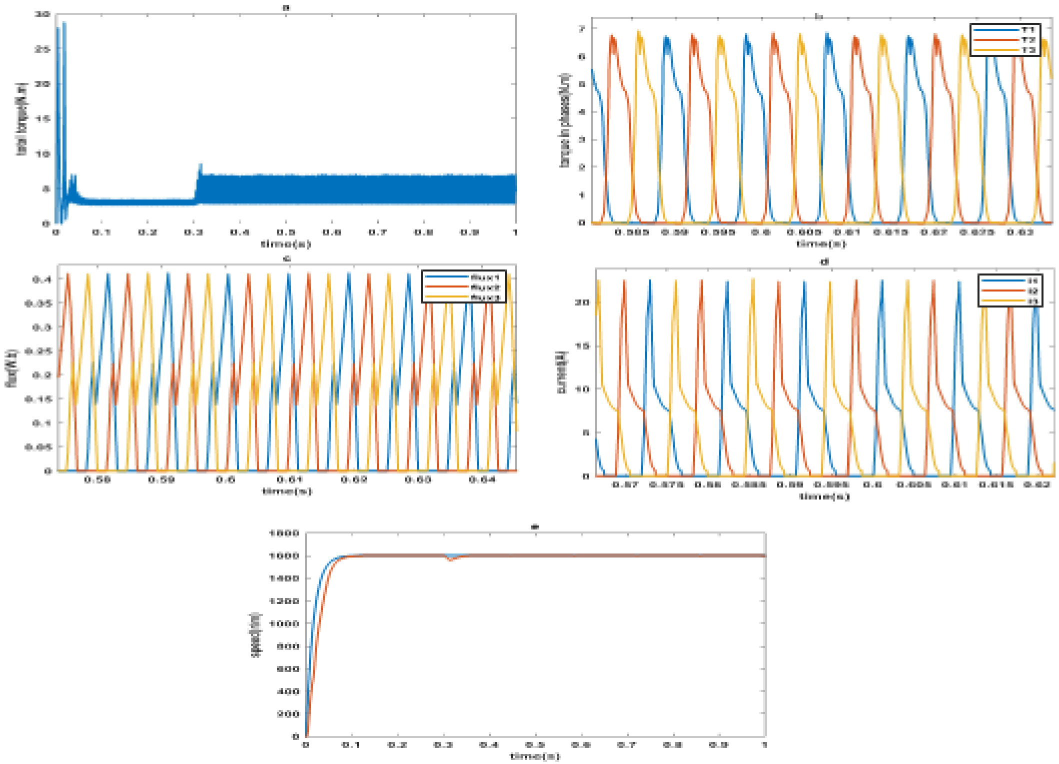

FIG. 7. **Simulation result of DFC (a: total torque, b: torque in phases, c: flux, d: current,e:speed)**

Comparison with deferens methods

Throughout this section, the motor is operated at various speeds for each of the methods (DTC, DEC, DFC and proposed method DEFC) that were examined in order to compare them and determine which produces the least torque ripple. Utilizing this relationship to determine the torque ripple factor Trf, we can determine the torque ripple ratio.

$$Trf = \frac{T_{\max -}T_{\min}}{Tav}$$

So that Tmax represents the maximum torque, Tmin the minimum torque and Tav is the average torque. The following tables represent the simulation result of the DTC, DEC,

DFC and proposed method DEFC so that the SRM workat deferent speeds (2200, 2000, 1800, 1600, and 1400 t/m), at every speed we take the total torque, torque in phases, current and flux and we calculate the torque ripple factor to determine the effectiveness of the deferent methods of control. In comparison we note that the proposed method DEFC gave us the lowest torque ripple factor, at speed 2200 r/m the Trf =37% but in DTC the Trf =70% and in DEC 39%, in DFC 44%. At 2000 r/m the torque ripple factor is giving as follows in DEFC 31%, DEC 42%, DFC 34% and DTC 55%. The torque ripple factor at speed 1600r/m in DEFC, DEC, DFC and DTC in on the order 10%, 13%, 14%, 31%. we also note that the SR motor provided the lowest value of the torque ripple factor in speed 1600r/m this is for all methods studied in this work.by comparing the results of deferent method we conclude that the proposed method DEFC was presented the best efficiency of the SRM and reduced torque ripple to a good ratio that makes the switch reluctance motor with low vibration **TABLES 2-5 and FIGURE 10**.

TABLE. 2. Torque ripple factor of DTC

Speed (t/m)	Total torque (N.m)	Torque in phase (N.m)	Current (A)	Flux (Wb)	Trf (%)
2200	5,34	5,42	17,2	0,395	70
2000	4,6	4,72	17,15	0,38	55
1800	3,9	4,15	17	0,382	36
1600	3,4	3,53	13,4	0,4	31
1400	3,42	3,45	7,15	0,45	43

TABLE. 3. Torque ripple factor of DEC

Speed (t/m)	Total torque (N.m)	Torque inphase (N.m)	Current (A)	Flux (Wb)	Trf (%)
2200	5, 6	5, 7	15, 95	0, 415	39
2000	4, 9	4, 87	16, 4	0, 409	34
1800	4, 15	4, 1	20, 1	0, 435	26
1600	3, 4	3, 38	10, 4	0, 43	14
1400	3, 6	3, 58	7, 5	0, 48	37

TABLE. 4. Torque ripple factor of DFC

Spe ed (t/m)	Total torque (N.m)	Tor que in pha se (N.m)	Cu rrent (A)	Flu x (Wb)	Trf (%)
2200	6, 4	6, 15	16, 5	0, 385	44
2000	5, 5	5, 25	13, 2	0, 387	42
1800	4, 5	4, 4	17, 5	0, 386	27
1600	3, 4	3, 4	1 6	0, 39	13

1400	3, 65	3, 6	7, 4	0, 452	39

TABLE. 5. Torque ripple factor of DEFC

Spe ed (t/m)	**Total torque (N.m)**	**Tor que in pha se (N.m)**	**Cu rrent (A)**	**Flu x (Wb)**	**Trf (%)**
2200	5, 8	5, 85	16, 4	0, 39	37
2000	5	5, 05	17, 05	0, 385	31
1800	4, 2	4, 23	17, 4	0, 383	23
1600	3, 3	3, 28	15, 8	0, 395	10
1400	3, 55	3, 56	7, 6	0, 475	35

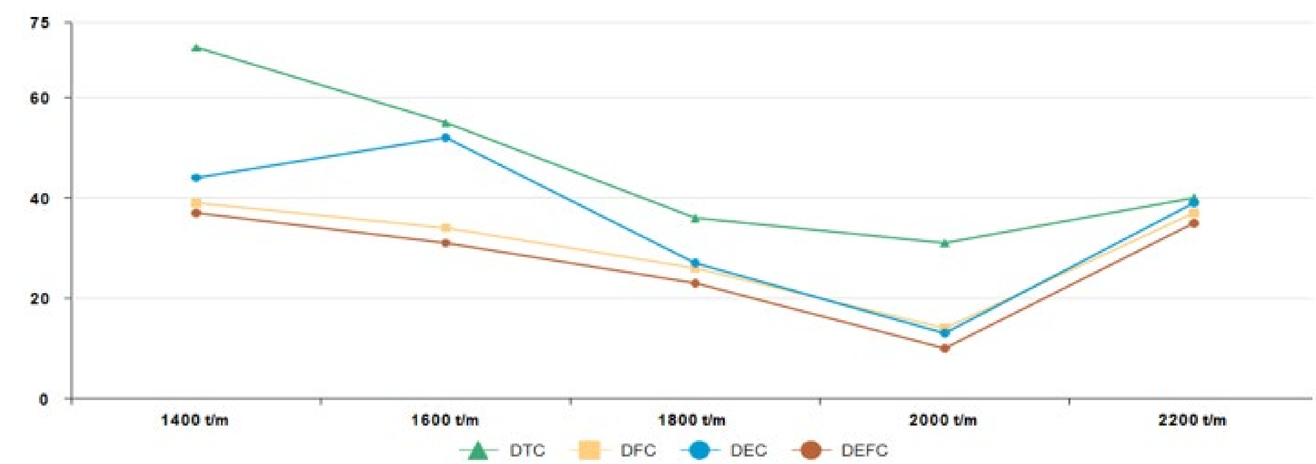

FIG.10 **Torque ripple factor**

Conclusions

This paper presents a new control method for Switched Reluctance Motors (SRM) called Direct Force and Energy Control (DEFC). The purpose of this method is to reduce engine torque fluctuations and vibrations that can have a significant impact on engine efficiency and performance. Unlike traditional Direct Torque Control (DTC), the DEFC method uses dual control of force and energy, providing a more effective approach to reducing torque fluctuations and vibrations. His proposed DEFC method was verified by the simulation results of his SRM model. Torque ripple reached 36% with the conventional DTC method, while it was approximately 10% with the DEFC method. This significant reduction in torque ripple highlights the effectiveness of the DEFC approach in improving motor efficiency and reducing vibration. To further confirm the usefulness of the proposed DEFC approach, a comparative analysis with other established control methods such as Direct Energy Control (DEC) and Direct Force Control (DFC) was performed. The comparison results show that the DEFC method outperforms the traditional approach in reducing torque ripple and improving SRM efficiency. In summary, the proposed DEFC method provides a new and effective approach to control SRM. Dual control of force and energy directly replaces torque and flow, greatly reducing torque ripple and vibration. The results of the comparative analysis highlight the superiority of his DEFC approach over previous methods, and we believe that this method has great potential to improve the performance and efficiency of his SRM in various applications.

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