Acta
Technica
Jaurinensis

Vol. 12, No. 2, pp. 101-116, 2019
DOI: 10.14513/actatechjaur.v12.n2.496
Available online at acta.sze.hu

Direct Instantaneous Torque Control of the Switched Reluctance Motor for Electric Vehicles Applications Using Fuzzy Logic Control

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Abstract: This paper presents direct torque control of Switched Reluctance Motor (SRM) using Fuzzy Logic Control (FLC) for electric vehicles applications. The PD-FLC is proposed for SRM torque control, to keep the torque of the motor shaft in tracking the reference torque with high accuracy. With the help of FLC techniques, the SRM torque ripples can be reduced compared to traditional control techniques. In this study, the nonlinear 6/4 SRM model is simulated with the symmetrical converter, and the converter controller is programmed using C-language. The proposed method is tested at different load and variable speed conditions, and the obtained results confirm that the FLC direct torque control can be used for torque control to improve the motor performance and reduce the torque ripples compared to other techniques such as direct instantaneous torque control.

Keywords: switched reluctance motor, electric vehicles, fuzzy logic control, control techniques, torque control, and torque ripple

1. Introduction

In the present, the energy sources, environmental pollution, and noise are considered the main problems facing many countries due to using conventional vehicles [1]. In contrast, the Electric Vehicles (EVs) provide a good solution for pollution and noise problems and reduce petroleum usage as well. Therefore, the using of the EVs in transportation became essential consequently, the EVs proportion in the commercial market gradually increasing [2][3]. Recently, researchers and industrial companies are working to solve the operational problems of EVs, save energy, and achieve the best performance at an appropriate cost. To improve the overall performance of the EVs many different components must be optimized, the electric motors and it's driving circuits are considered the main components and the most important parts in the EVs therefore, the performance of the vehicles depends mainly on electric motors and driving circuits [4][5].

There are many types of electric motor that can be used for EVs applications each type has advantages and drawbacks. The Switched Reluctance Motors (SRMs) are considered one of these types that can be applied to EVs, due to their several advantages such as low-cost manufacturing, simple construction and material composition, high starting torque, rugged construction, high speed ranges, ability to operate at high temperature, higher reliability, and low inertia. Although the SRM has many benefits, still face some drawbacks and challenges which have to overcome such as torque ripples due to doubly salient structure and pulse excitation, and complex control [6][7]. To overcome the problems of the SRM and improve the EVs overall performance there are two main ways, the first one by improving the mechanical design of the electric machine and the second way by selecting suitable control strategies and optimal control techniques. Three main strategies can be used for SRM control these strategies are speed control, current control, and torque control [8]. The main challenge which has to be solved by control techniques is the torque ripples problem, this problem is considered very complicated, and it is not easy to solve because it is affected by many factors [9].

Two types of torque control strategies can be used for SRM: the first strategy is indirect torque control, which uses the complex algorithms or distribution function to obtain the reference current. After that, the current controller is used to control phase torque. The second strategy is the Direct Torque Control (DTC) which uses the torque controller and simple control scheme to reduce the torque ripple [10]. In recent years, the Direct Instantaneous Torque Control (DITC) algorithm has much progress and development to overcome the problems of the indirect torque control methods [11]. The main feature of this method is the instantaneous torque is considered a control variable directly, and the conversion from torque to current and closed-loop currents control became not essential. Also, DITC able to avoid the torque error immediately with a good dynamic response and reducing the torque ripple [12]. Because of the simple hysteresis switch rule is used in the traditional DITC method, just one phase state can be used depending on the error in the torque at each sampling cycle. Two different methods can be used to make sure that the torque ripple within an acceptable range: the first method is the sampling time reduction but this solution maybe increases the hardware cost, and the second method is the PWM method which can be used to control of the average voltage of phase winding in sampling time [10].

Recently, the applications of artificial intelligence methods have been used to translate human knowledge into a form comprehensible by computers. Advanced control based on artificial intelligence techniques is commonly defined as intelligent control. The intelligent control methods considered one of the applicable technique that can solve the torque ripple issue in the SRM, because of the advantages of intelligent control such as nonlinear control, self-learning, and it is adaptive capacity. The idea of intelligent control is to use off-line or online learning and optimization. Fuzzy Logic Control (FLC) is a technique to make machines more intelligent, it is defined as a mathematical tool to deal with uncertainty and imprecision [13], it was introduced by Lotfi Zadeh in 1965 [14], and it is one of the artificial intelligence methods which suitable for torque control of SRM. FLC system consisted of three main blocks as shown in Fig. 1 [15]. The first one is fuzzification its main function converts the input data to fuzzy sets values. The second block is decision making logic depend on the knowledge base, this part determines how the logic operations are achieved, and together with the knowledge base can regulate the outputs of each fuzzy set. The last one is the defuzzification block, which converted fuzzy values to output data [16], [17].

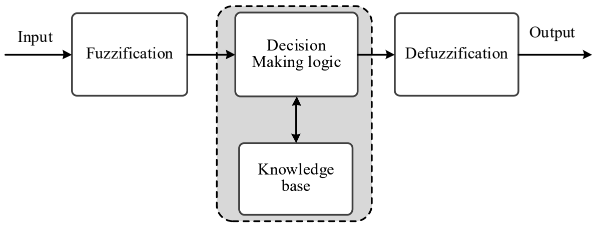

Figure 1. The fuzzy logic system block diagram

2. Direct instantaneous torque control

The online availability of the total instantaneous torque is considered fundamental requirement for the DITC strategy, and due to the nonlinear characteristics of the SRM it is not easy to obtain the instantaneous torque by straightforward analytical equations as in other motors (DC or rotating field) but the instantaneous torque can be estimated only by stored characteristics of the motor [18]. Two methods can be used to estimate the instantaneous torque, torque estimation as a function of phase current and rotor position, or estimate the torque as a function of phase current and phase flux linkage [10]. Fig. 2 show the overall blocks diagram of the current-position based DITC.

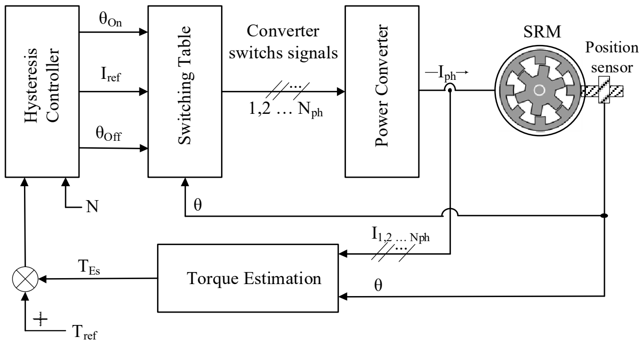

Figure 2. Direct instantaneous torque control

The PWM-DITC consisted of a combination of the traditional DITC and PWM as shown in Fig. 3 [19]. Depending on the phase currents (Iph) and rotor position (θ) the lookup table is used to implement the torque estimation block. The torque control block generating the duty cycle for all activated motor phases depending on the error between the estimated torque and command torque, then the PWM block generate the switching signals for the power converter. By using the PWM method the average phase voltage can be regulated to control the currents variety in single sampling time, the sampling time can be extended and reduce the torque ripple comparing to the traditional DITC. The significant drawback of this method the switching frequency is increased comparing to DITC therefore, the losses due to switching frequency and EMC noise are increased.

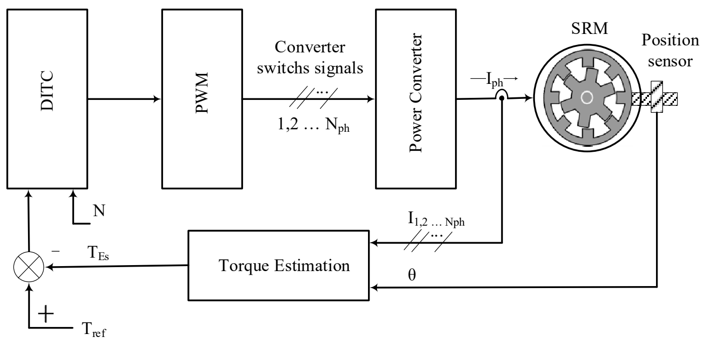

Figure 3. Direct instantaneous torque control with PWM

3. Controller design

To programming the FLC, there are main steps have to be performed: Firstly, classify the inputs, their ranges/limits, and label them. The second step is to classify the outputs. Thirdly, make the degree of the membership function for every input and output. After that, structure the system rule-based and determine how the action will be performed by select optimum rule-based. Finally, combined the rules and defuzzify the output. In this study, PD-FLC is proposed for DITC to enhance motor performance and reducing the torque ripples compare with the DITC method. The inputs of the FLC are the motor shift torque error (e) and the change in this error (Δe). The output of the FLC is a converter modulation index, which used to generate the optimal gating signals after comparing it with a carrier wave in the PWM block as described in Fig. 4 the FLC design steps will be discussed in the following sections.

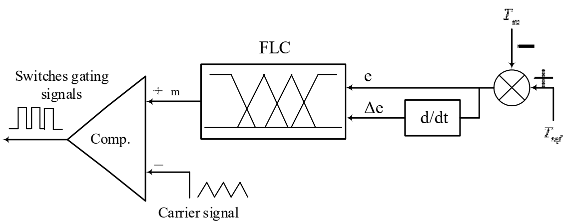

Figure 4. PD-Fuzzy logic direct torque control

3.1. Fuzzification

The FLC uses linguistic variables instead of numerical variables, and the fuzzification process converts these numerical variables (real numbers) to linguistic variables (fuzzy sets). Consequently, the motor torque error signal values can be assigned as follow: Negative Very Big (NVB), Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), Positive Big (PB), Positive Very Big (PVB). The shape of the membership function for the first input is shown in Fig. 5. Similarly, the second input for the fuzzy system (change of error) converted from numerical value to a linguistic variable according to the membership function shown in Fig. 6.

3.2. Rule Evaluator

The membership functions variables were defined off-line, and its values are selected according to the behavior of the system observed during simulations. The decision-making logic (rules base table) which used in this work are listed in Table

1, and it can be built using the experiences and by observing the performance of the controller. Generally, to evaluate between two inputs (A and B) the basic fuzzy set operations can use one of three rules AND (∩), OR (∪) or NOT (~). In this work, AND (∩) intersection is used which is presented in equation (1) [20].

$$\mu A \cap B = min\,[\mu A\,(X), \mu B\,(X)] \tag{1}$$

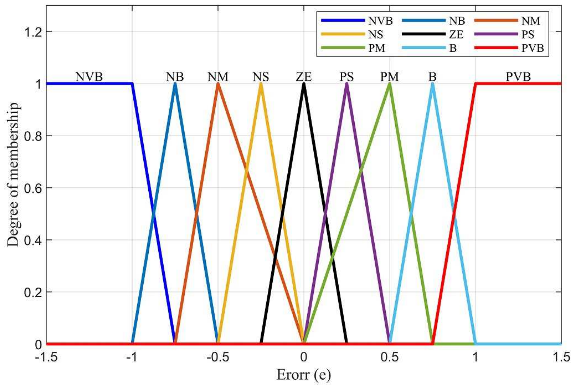

Figure 5. Membership functions representing the error signal

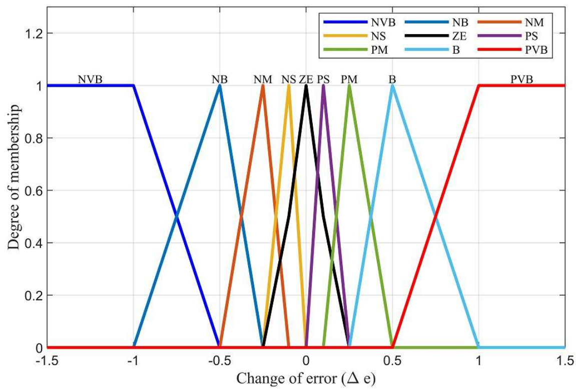

Figure 6. Membership functions representing the change of error

Table 1. If-Then rule base for fuzzy logic control

Δe \ e	NVB	NB	NM	NS	ZE	PS	PM	PB	PVB
NVB	EL	EL	EL	EL	EL	VL	L	UM	M
NB	EL	EL	EL	EL	VL	L	UM	M	AM
NM	EL	EL	EL	VL	L	UM	M	AM	H
NS	EL	EL	VL	L	UM	M	AM	H	VH
ZE	EL	VL	L	UM	M	AM	H	VH	EH
PS	VL	L	UM	M	AM	H	VH	EH	EH
PM	L	UM	M	AM	H	VH	EH	EH	EH
PB	UM	M	AM	H	VH	EH	EH	EH	EH
PVB	M	AM	H	VH	EH	EH	EH	EH	EH

3.3. Defuzzification

The function of the defuzzification step is convert-back linguistic variables of the output, which generated from fuzzy logic rules to real numbers. The membership function shape for defuzzification process which used in this study is shown in Fig. 7. In this case, the output signal which represents the modulation index (m) can be assigned as follow: Extremely Low (EL), Very Low (VL), Low (L), Under Medium (UM), Medium (M), Above Medium (AM), High (H), Very High (VH), Extremely High (EH).

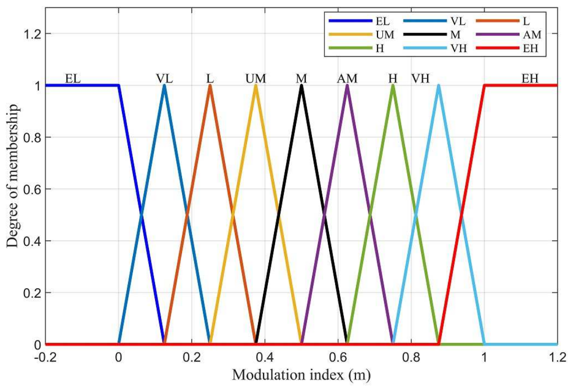

Figure 7. Output Membership functions

Three different methods can be used for membership defuzzification, Center Of Area (COA), Bisector, or Middle Of Maximum (MOM). In this study, the COA method is used, which is presented in equation (2), because it considered the most popular method [20] [21].

$$U(n) = \frac{\sum_{j=1}^{n} \mu(uj)\omega j}{\sum_{j=1}^{n} \mu(uj)}, \tag{2}$$

where μ(uj) the membership function of the jth fuzzy set of input variable uj, and ωj the jth output fuzzy, and n is the number of fuzzy membership functions.

4. Simulation results and discussions

The SRM torque control with the PD-FLC control technique is shown in Fig. 8. The controller needs a reference torque signal to be followed by the motor torque, for this reason, the motor speed is taken as the feedback signal and compared to the desired speed and determine the error values of the motor speed, this error is applied to the PI controller to generate the demanded reference torque. With the help of the phase current and rotor position, the motor shaft torque can be estimated, the most general expression for the instantaneous torque equation of the of SRM can be expressed in equation (3), the estimated torque compared to reference torque, the torque error and the change in this error are used as input variables for FLC. According to the controller design, the controller determines the degree of the modulation index of the power converter then the PWM block generates the switch-state for all active switches of the power converter.

$$T_j = \frac{dW_C(\theta,i)}{d\theta}\Big|_{i_j=const} = \frac{dW_S(\theta,i)}{d\theta}\Big|_{\psi_j=const} \tag{3}$$

where T_j is the phase torque, W_C is the co-energy, and W_S is the stored field energy.

The control technique proposed in this work is conducted on a 60 kW SRM using PSIM software [22], and the controller is programmed using a C-code capability in this software. The simulation parameters of the SRM are given in Table 2. [8] [23]. The first step of the simulation work is applying the DITC using Hysteresis Torque Control (HTC) for SRM and obtain the machine performance (motor speed profile, motor torque, and torque ripples). The simulation carried out through three steps: the first one is applying the conventional DITC using hysteresis control and observe the machine performance (motor speed profile, phase current, motor torque, and torque ripples). After that, in the second step, the DITC is applying but using PD-FLC instead of hysteresis control and observe the performance of the SRM. Finally, comparing the obtained results for the motor performance in step one and two are compared.

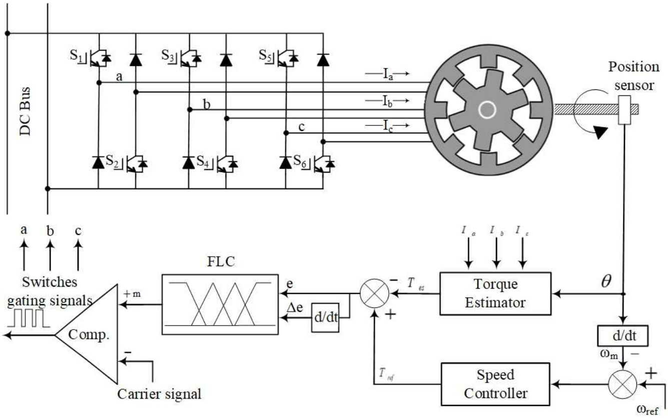

Figure 8. SRM torque control block diagram using PD-FLC

Table 2. SRM simulation parameters

Parameter	***Value***	***Parameter***	***Value***
Power	60 kW	Speed	1000 rpm
DC link voltage	220 V	Load torque	10 - 20 Nm
Maximum current	450 A	Inertia	0.05 kg m^2
Stator resistance	0.05 ohm	No. of rotor pole	4
Unaligned inductance	0.67 mH	No. of stator pole	6
Aligned inductance	23.62 mH		

To verify the effectiveness of the performance for the proposed controller, it is tested at two different study cases: the first one is investigating the controller robustness in following the reference torque, in this case, the reference speed is *1000 rpm*, and the load torque is changed from *10 Nm* to *20 Nm* at *0.3s*. The motor speed profile in case of load changed is shown in Fig. 9 the motor speed reaches to steady state after *0.05s* and tracks the reference speed until the load torque changed at *0.3s*, then a small drop in the motor speed occurs, this drop is not static and decreasing, but it needs more than 0.5s to reach the desired speed as shown in the zoom of the speed profile.

The SRM torque performance is studied using hysteresis control with sampling time $Ts=1\mu s$, and the hysteresis band was the smallest possible value with this sampling time ($\Delta T=\pm 0.5$). PD-FLC also is applied to the motor torque controller and the sampling time is constant in two control methods. The torque of the motor is shown in Fig. 10 and it's clear that the motor torque was doubled at *Ts=0.3s*, to investigate the controller robustness in track the reference torque. Also, this figure shows the comparison between the two used techniques at different load conditions, where the black color represents a motor torque using hysteresis control (HTC) and this torque is in red color in case of fuzzy control (FLC). This comparison shows that the torque ripples during the phase conduction period at two different load conditions with FLC are smaller than in case of hysteresis control. There is no doubt that the motor torque ripples still needed to reducing particularly in the phase commutation period, this period basically depends on the optimal turn on and turn off angle according to motor design parameters.

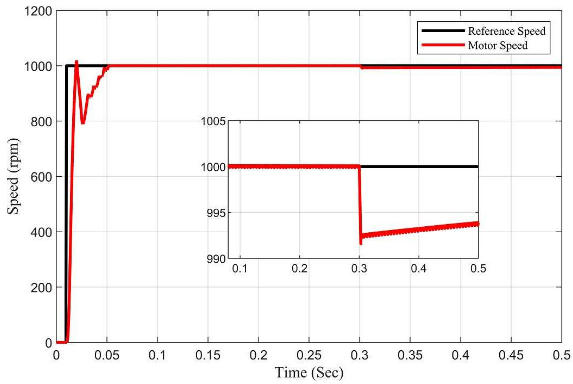

Figure 9. SRM speed profile in case of load torque changed condition

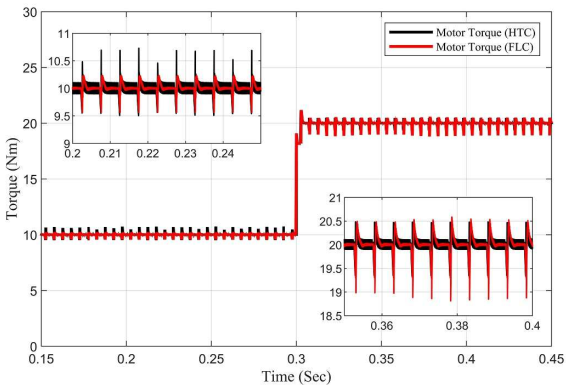

Figure 10. The motor torque with constant speed and load torque changed at 0.3s

The comparison between the motor phase current using FLC, and in the case of hysteresis control in case one is shown in Fig. 11. The obtained results show the difference between the two techniques, for phase (a) as an example the red color represents a phase current using hysteresis control, and this current is in blue color in case of FLC. It is noted that the current ripples during the phase conduction period using FLC are smaller than in the case of hysteresis control. This result shows the ability of the fuzzy logic technique to reduce the motor phase current ripples comparing to traditional methods.

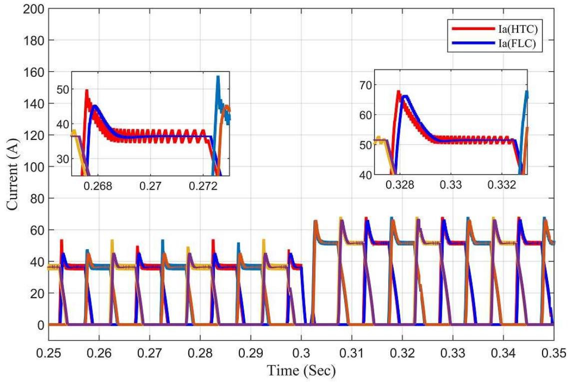

Figure 11. The phase current signals and zoom in case of load torque changed

The second study case tests the tracking performances of the controller, the motor speed profile, in this case, shows in Fig. 12 which load torque is *10 Nm* and the reference speed changed from *800 rpm* to *1200 rpm*, and the results show that the motor speed is tracking the reference speed satisfactorily. The motor torque in case of tracking performance is shown in Fig. 13 by zooming the motor torque performance curve it can be noted that the torque ripples in case of FLC are smaller than hysteresis control case at different speed values. When the motor torque increase to reach *20 Nm* with a variable reference speed, also the results demonstrate that the motor torque performance in case of FLC method for direct torque control is better than the conventional DITC methods. The obtained result at *20 Nm* load torque is shown in Fig. 14.

The previous results confirm that the proposed torque controller (FLC-DITC) has many advantages comparing with traditional DITC technique not only because of the general advantage of FLC as we mentioned in the introduction section but also this technique makes the motor torque tracked the reference signal with the smallest value of torque ripples at different loading conditions and variable speeds. Table 3.

reviews the torque ripples percentage by using FLC and hysteresis control, in case of reference speed *1000 rpm* and the load torque changed from *10 Nm* to *20 Nm*, and Table 4. reviews the torque ripples percentage, when, the reference speed changed from *800 rpm* to *1200 rpm* and the load torque *TL=10 Nm.* These tables summarize and demonstrate the effectiveness of the fuzzy logic DITC method compared to the traditional DITC method.

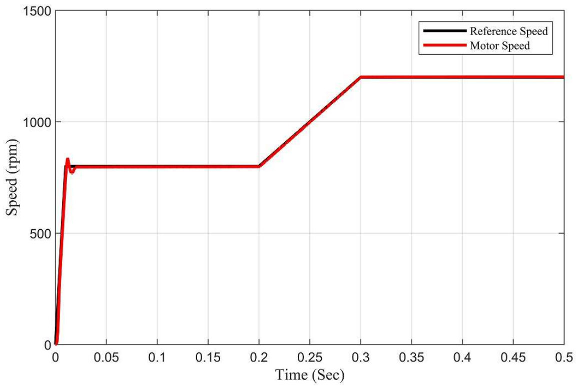

Figure 12. SRM speed profile with constant torque and reference speed changed

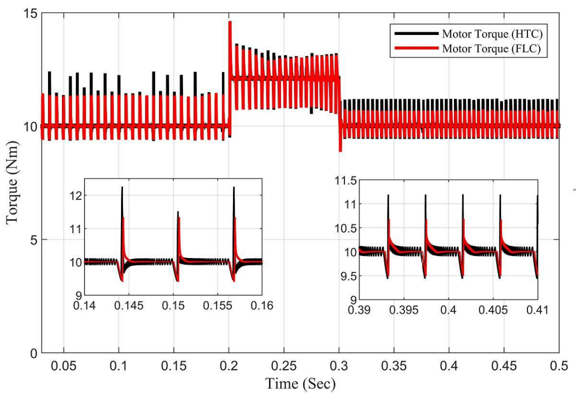

Figure 13. The motor torque in case of tracking performance (TL = 10 Nm)

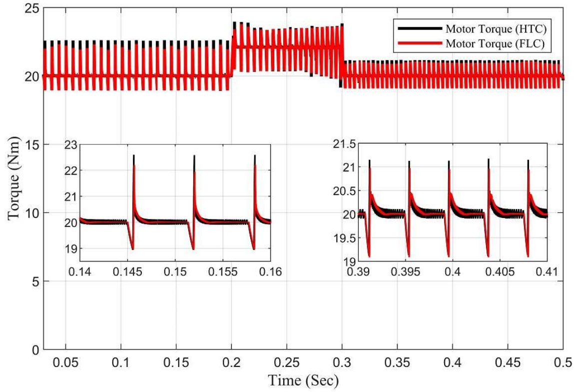

Figure 14. The motor torque in case of tracking performance (TL = 20 Nm)

Table 3. SRM torque ripples in case 1(Speed =1000 rpm)

Load Torque / Torque ripples	10 Nm	20 Nm
Fuzzy Logic DITC	6.9%	5.8%
Conventional DITC	12.3%	8.85%

Table 4. SRM torque ripples in case 2 (Torque = 10 Nm)

Motor Speed / Torque ripples	800 rpm	1200 rpm
Fuzzy Logic DITC	20.7%	12.5%
Conventional DITC	30.65%	17.8%

5. Conclusions

In this paper, fuzzy logic direct torque control of switched reluctance motor for electric vehicles applications was introduced. The FLC is one of artificial intelligence control techniques, and it is suitable for torque control of the SRM because it has many advantages such as nonlinear control, self-learning, and its adaptive capacity. In this work, the FLC programmed by C- code and the simulation test performed with 60 kW SRM. The controller was tested at different loading conditions to investigate the controller robustness, and with variable reference speeds to examine the tracking performance of the proposed controller. The obtained results show the effectiveness of the proposed technique (PD-FLC) to reduce the SRM torque ripples, whether in case of torque load changed or in case of motor speed changed. With the help of fuzzy logic DITC, the SRM torque tracking the reference signal with smaller values of ripples compared to traditional DITC techniques.

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