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Fuzzy Logic Current Control of Switched Reluctance Motor for Electric Vehicles Applications

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Abstract—This paper presents current ripple minimization of Switched Reluctance Motor (SRM) during phases conduction period by using Fuzzy Logic Control (FLC) for electric vehicles (EVs) applications. The FLC is applied for current control in SRM to keep the motor current value tracked the reference signal with minimum ripples in current, and hence the torque ripples will be minimized. The PI speed controller is used to generate the reference current signals depending on the command motor speed. In this study, the nonlinear model of 6/4 SRM is used in a simulation with symmetrical converter, and the controller is performed on C-code. The response of the proposed controller is studied under different loading conditions, and the obtained results verify that the FLC is an efficient control technique for the SRM current control compared to traditional techniques such as Hysteresis Current Control (HCC).

Keywords— Electric Vehicles (EVs); Switched Reluctance Motor (SRM); Fuzzy Logic Control (FLC); Control Techniques; Current Control; and Torque ripple.

1. INTRODUCTION

Recently, many countries face a lot of challenges regarding energy, environmental pollution, and noise problems, which generated from conventional vehicles [1]. In the past few decades, Electric Vehicles (EVs) have become increasingly important in transportation and essential to reduce dependence on oil and minimize noise and pollution, so the EVs increasing their proportion in the commercial market [2].There are many components in EVs, these components require being optimizing to improve the EVs efficiency, such as sizing, electric motors, drive circuit and its control techniques, and power supply. The electrical motors are considered the major part of EVs and one of the most important components [3]. The performance and efficiency of the motors have a great and direct effect on EVs performance; therefore, there is a need for high-performance motors [4][5].

Because of their several advantages, the Switched Reluctance Motors (SRMs) have been applied to EVs. The most significant advantages of SRMs are Low cost manufacturing, simple construction and material composition, high speed ranges, can operate at high temperature, higher reliability, low moment of inertia, and skewing is not required, so, the SRM is very suitable for EVs applications due to rugged construction, large starting torque, and wide speed range [6]. However, some disadvantages must be mentioned, like their complex control, and torque ripples due to doubly salient structure and pulse excitation [7].

The SRMs overall performance can be improved by two main ways. The first way by improving the mechanical design, and second one by the control techniques. There are different types of control strategy can be applied on SRM such as speed/position control, current control, and direct/indirect torque control [8]. The torque ripples consider the main challenge of the SRM in many applications particularly in EVs applications, this problem is very complicated and affected by many factors and it is not easy to solve [9]. Different strategies of control are used to overcome of this problem like traditional control strategy, torque distribution strategy, linearization control, intelligent control, and other control methods. So, by selecting the suitable control strategy for each application, the torque ripple can be efficiently decreased [10].

The SRMs can be run in current or voltage control mode. The voltage controlled of SRM is high sensitive to voltage ripple on the supply side and its bandwidth control is lesser, so it is essential to use current control when SRM performance is desired to an accurate torque control [10]. In this work the current control of SRMs is applied with using of intelligent control strategy for current and torque ripples minimization. The intelligent control strategy which used in this study is Fuzzy Logic Control(FLC). FLC is a technique to make machines more intelligent, fuzzy logic tool was introduced by Lotfi Zadeh (1965) [11], and the FLC defined as a mathematical tool to deal with uncertainty and imprecision. FLC provides outstanding advantages over the conventional controllers such as easiness to develop, cover a wider range of operating conditions, and more readily customizable in natural language terms [12].

2. CURRENT CONTROL FOR SRMs

The speed controller usually used to generate the reference current signal for current controller depending on the different between the feedback actual speed (ω_m) and the reference speed (ω_{ref}). the feedback actual speed is measure by speed sensor or calculate from rotor position [13][14].The calculated speed error signal is used as input variables to speed control block, which usually is PI(D) controller as shown in Fig. 1. The speed control output signal used as a reference signal for current controller [15][16], the commutation block diagram is used to distribute the reference current signal and generate the reference current signal for each phase. After that the generated reference current compare with the actual one and the error between them used as input variable to current controller, the current controller will determine the on and off period for each switch of the power converter according to the current error signals, and each phase position data.

The SRM current controller can be implemented by two different methods, first method is Hysteresis Current Control (HCC), which used ON-OFF control rules, it will be required high switching frequencies electronics elements [17][18]. The most significant advantage of this method is very easy to implement with analog elements and robustness. But there are some drawbacks of this kind of control [19], it causes residual current ripple, and the switching frequency in this method may be always variable and unknown, the HCC mechanism shown in Fig. 2.

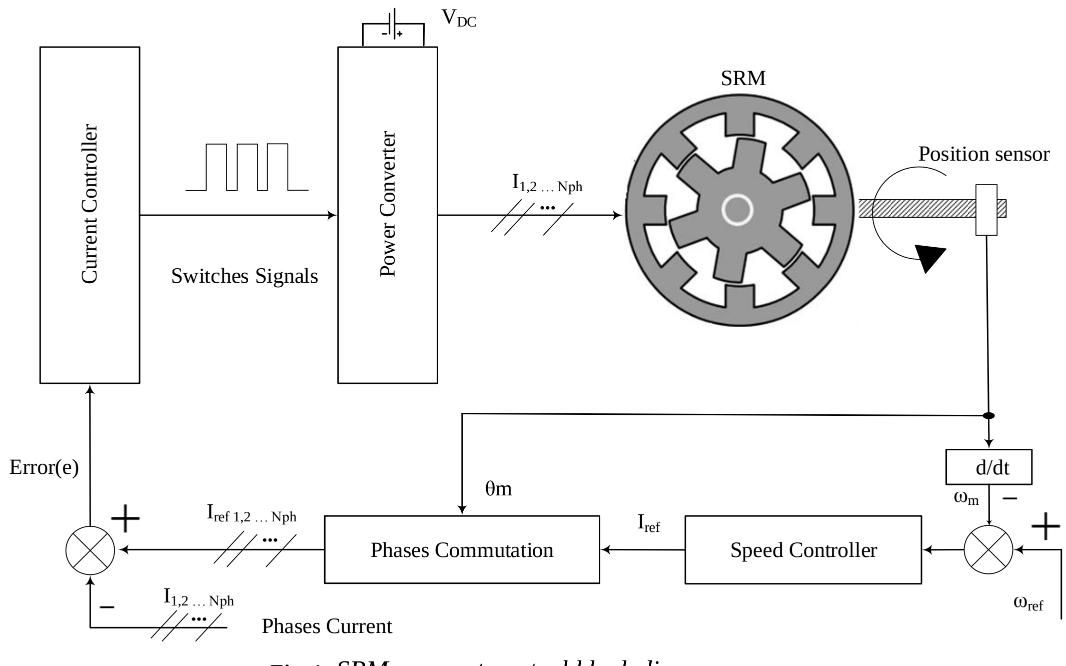

Fig. 1. *SRMs current control block diagram*

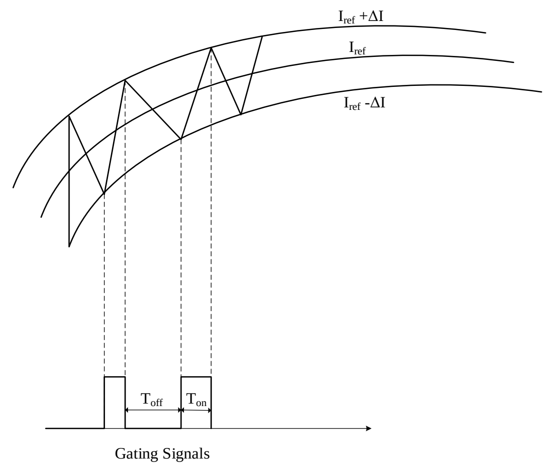

Fig. 2. *Hysteresis current control (HCC) mechanism*

The other method that can be used in the SRMs current controller is Pulse Width Modulation (PWM) current control [20], the PWM controller calculates the duty cycle (ON and OFF) times by comparing the modulation index which generated from current controller with a sawtooth or triangular carrier wave form as shown in Fig. 3. In PWM technique the current is controlled by the sampling time and filtered to smooth the current ripple which generated from the switching frequency, in this method the switching frequency will be known and controllable. PWM can be implemented easily with digital implementation and analog as well. Generally, the digital controller helps to improv the overall system performance by using different algorithms [21][22].

3. FUZZY LOGIC CONTROL APPROACH

Unlike conventional control systems, the FLC is able to model inaccurate or imprecise models. The fuzzy logic approach offers a simpler, quicker and more reliable solution than conventional techniques. The FLC has three main blocks. The first one is Fuzzification block, which modifies crisp inputs (input values from real world) into linguistic variables to enable the input physical signal to use the rule-base through membership functions. The second block is Rule-base, where fuzzy inputs are compared, and the controller makes the decision based on the membership functions of each input. The last one is Defuzzification block, which converts back the fuzzy outputs of the rule-base to crisp ones and selects membership functions for the different control outputs from the rule-base [23][24][25]. Fig. 4 show the components of FLC.

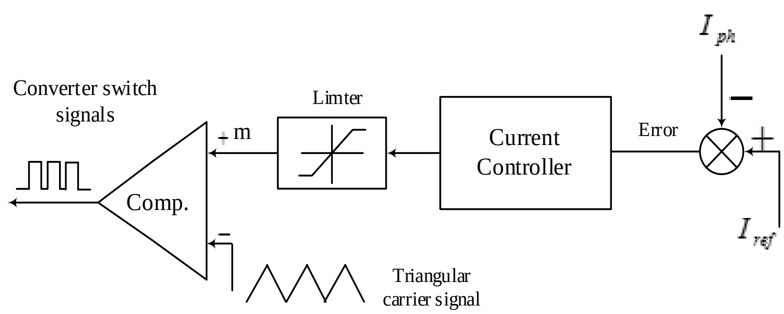

Fig. 3. *PWM Current Control Method of SRM.*

To programming the FLC, some steps will be performed: Firstly, classify the inputs and their ranges/limits and label them. The second step is classified the outputs and their ranges/limits and label them. Thirdly, make the degree of membership function for every inputs and output. After that, structure the system rule-based and determine how the action will be performed by select optimum rule-based. Finally, Combine the rules and defuzzify the output.

4. FUZZY LOGIC CURRENT CONTROLLER DESIGN

The FLC is proposed for SRM current controller in this study is to enhance the current regulation by reducing the current ripples compare with HCC method. The inputs of the FLC are the current error (e) of each phase Iph(t) and the change in this error (Δe). The output of the FLC is a modulation index (m), which used to generate the optimal gating signals after comparing it with carrier wave in PWM block as described in Fig. 5. In the following sections the FLC design steps will be discussed in detail.

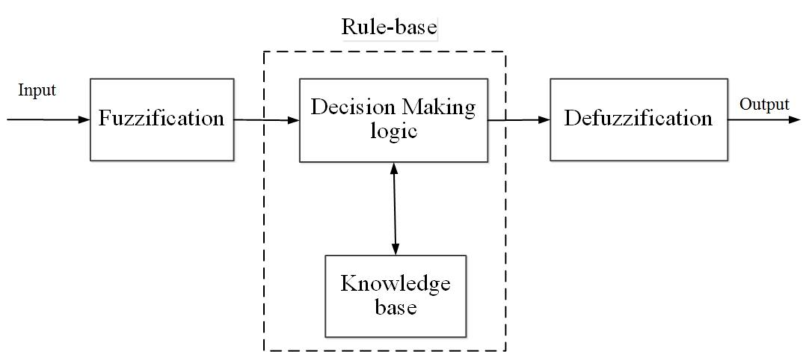

Fig. 4. *Fuzzy logic system components*

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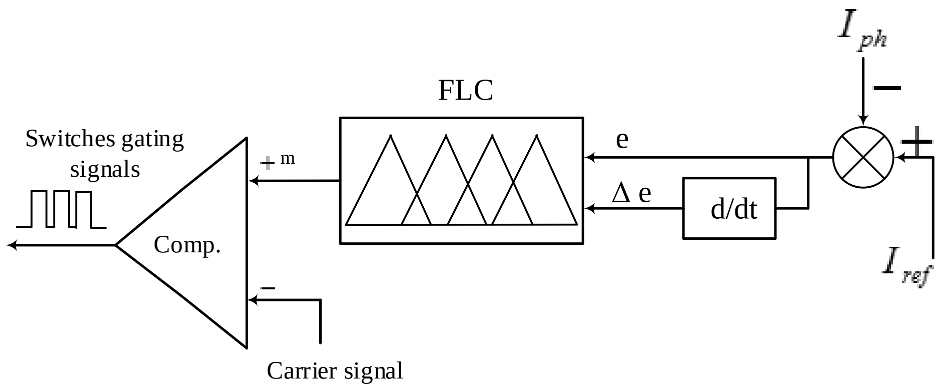


Fig. 5. *Fuzzy logic current control*

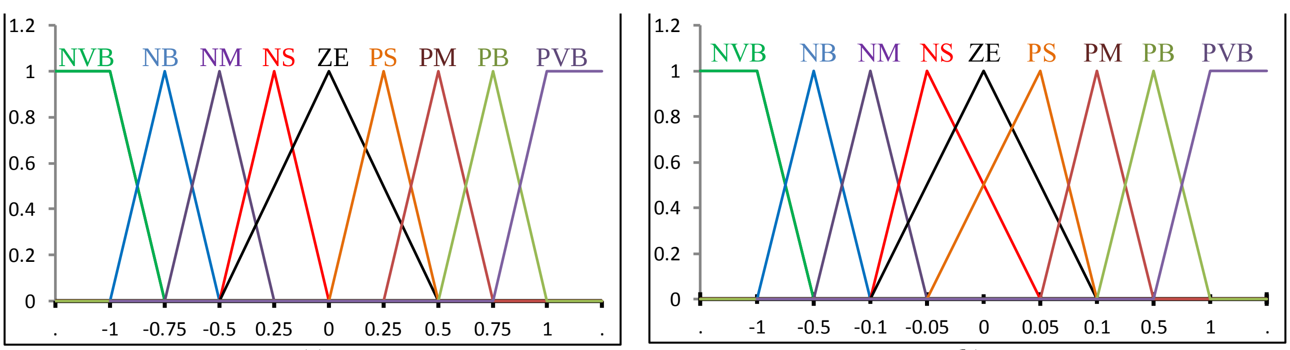
4.1 Fuzzification

This is considered the first step to be programmed, the FLC uses linguistic variables instead of numerical variables. So, the error input signals can be assigned as 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 triangular membership function is used for fuzzification as shown in Fig. 6 (a). The process of fuzzification convert numerical variable (real number) to a linguistic variable (fuzzy set). The change of error, which used as the second input for fuzzy system also converted from numerical value to a linguistic variable according to the triangular membership shown in Fig. 6 (b). It is noted that there are differences between error and change of error membership, this is in order to get the best performance from the controller.

4.2 Rule Evaluator

The input linguistic variables represent the degree of current error and change of error signals, while the output linguistic variables represent the degree of modulation index. The membership functions were defined off-line, and the values of the variables are selected according to the behavior of the variables observed during simulations. The basic fuzzy set operations needed for evaluation between two inputs (A and B) can use one of three rules of AND (∩), OR (∪) or NOT (~). In this work, AND-intersection are used which is presented in Equation 1 [25]. The rules base (decision-making logic) used in this work are listed in Table 1. It is worth mention here that this table is symmetrically diagonal about the membership function Medium (M).

$$\mu\, A\cap B = min\,[\mu\, A\,(X),\, \mu\, B\,(X)] \qquad (1)$$



(a) (b)

Fig. 6. *Membership functions representing the input signals (a) the error signal (b) the change of error*

Table 1: If-then rule base for fuzzy logic control

E \ CE	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

4.3 Defuzzification

The fuzzy logic rules generate the demanded output in a linguistic variable, these variables must be transformed to crisp output (real number). This step is the defuzzification, the membership functions used in this study for defuzzification are shows in Fig. 7. The output signal can be assigned as: Extremely Low (EL), Very Low (VL), Low (L), Under Medium (UM), Medium (M), Above Medium (AM), High (H), Very High (VH), Extremely High (EH), which represent the modulation index (m), where ($0 \leq m \leq 1$). There are three different methods can be used for membership defuzzification, Center of Area(COA), Bisector, or Middle of Maximum (MOM). The center area (COA) is considered the most popular method, so it is used for defuzzification in this study, which is presented in Equation 2 [23][25]:

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

where $\mu(uj)$ 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 ($n = 9$ in this case).

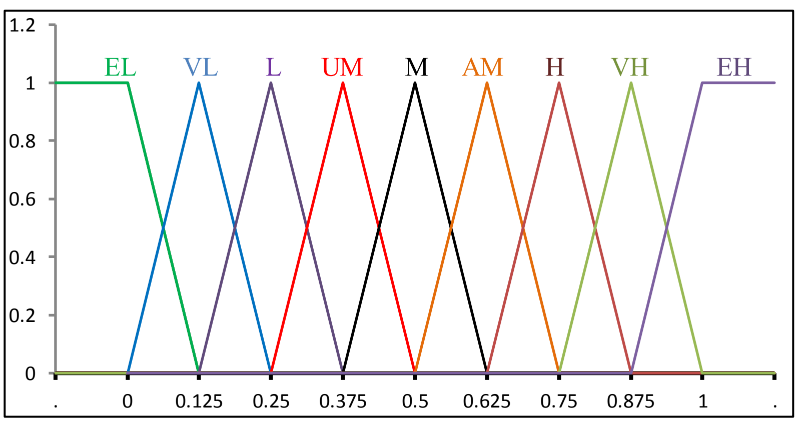


Fig. 7. *Membership functions representing the degree of modulation index (m).*

5. SIMULATION RESULTS AND DISCUSSIONS

The studied system is implemented in PSIM software [26], and the FLC control is carried out using a C-code capability in software, and the results are compared with HCC. The simulation is conducted on a 60 KW SRM, the motor parameters are given in Table 2 [8]. Simulation test divided to two main sections, the first one is the speed control of SRM using PI controller to generate the reference current signal for proposed controller from the speed error, and the second section is applying the FLC to SRM and compare the result with HCC.

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 mm
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		

5.1 SRM Speed Control

The SRM is tested with constant speed at 1000rpm and the load torque changed from 10nm to 20nm at 0.3 Second as shown in Fig. 8. The motor speed response and zoom of these signals are shown in Fig. 9(a and b) respectively with three different turn on angle (θ_{ON} = 90°, 100°, and 115°), where $90 \le \theta_{ON} < 120$. The main function of PI speed controller is keep the actual speed as close as possible to the reference speed (1000 rpm) in two load conditions and generate the reference current to produce suitable torque.

From the speed controller obtained simulation results, the speed response signals for three turns on angles are close to the reference one, but the best performance when the turn on angle between 100° and 115°, so the current controller is testing with a refence current generated from speed controller at θ_{ON}=100° and 115°. It worth to mention that this generated reference current is used for proposed current controller method (FLC), and traditional current controller method (HCC) as well. The generated reference current is shown in Fig. 10.

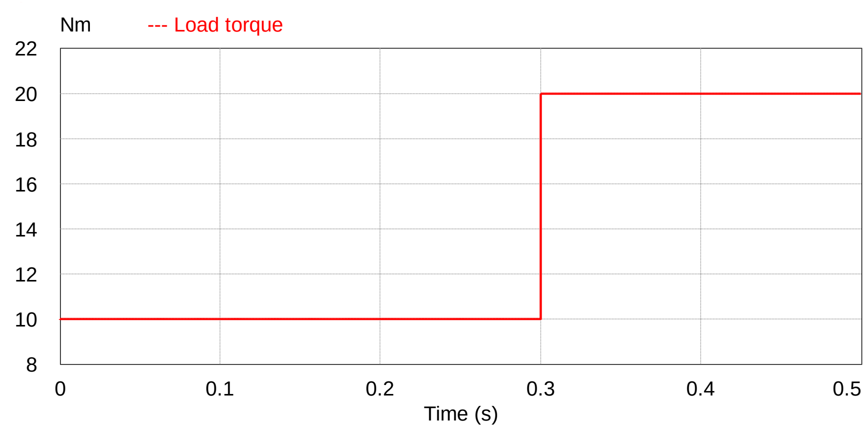


Fig. 8. *Load torque profile.*

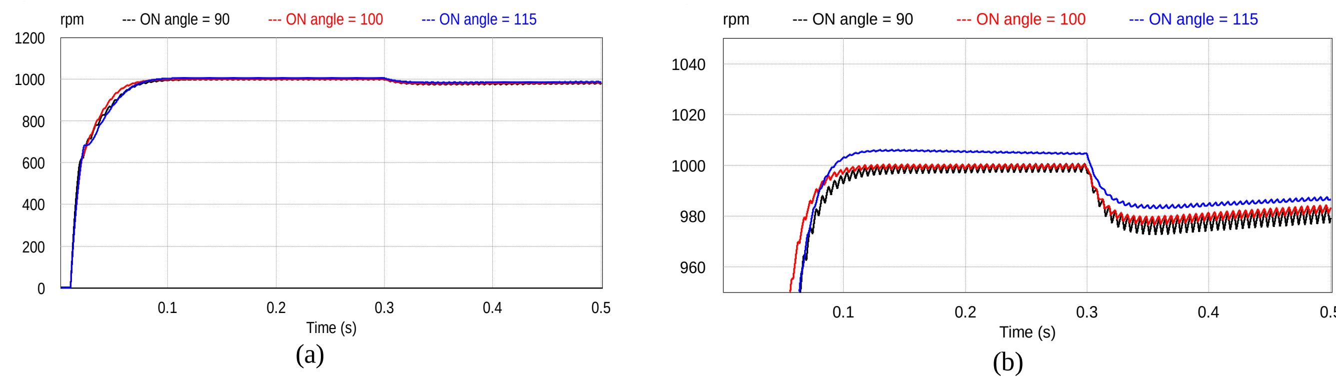


Fig. 9. *Motor speed profil (a) with θ_{ON} = (90°,100°,115°), and (b) Zoom of the motor speed.*

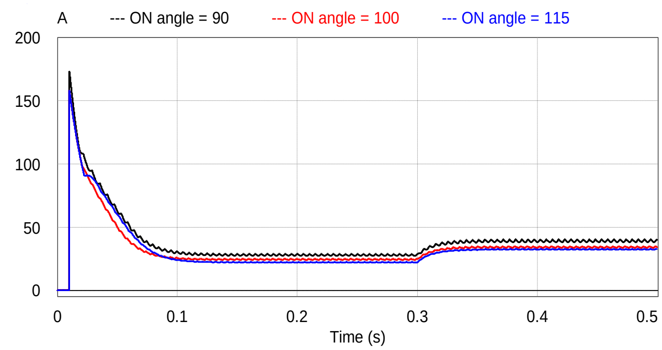


Fig. 10. *The generated reference current with θ_{ON} = 90°, 100, and 115.*

5.2 SRM Current Control

As mentioned before, the reference current generated from speed control loop used an input control variable to both current control methods HCC and FLC. To sure the effectiveness of proposed control techniques the sampling time is being constant in two control methods (Ts=1μs), and the hysteresis current band was the smallest possible value with this sampling time (ΔI=±0.5). Fig. 11 present the one phase current and the SRM torque with θ_{ON}=100° using FLC methods.

The comparison between current response using FLC and using HCC at θ_{ON}=100° shown in Fig. 12. For more detailed description, one phase current of SRM is zooming to show the different between two techniques, the red color represents a phase current using HCC, and the blue one in case of FLC, and the reference current signal generated from speed controller in black color. It is noted that the current ripples during phase conduction period in FLC smaller than in HCC. As mentioned before the sampling time is constant in two methods.

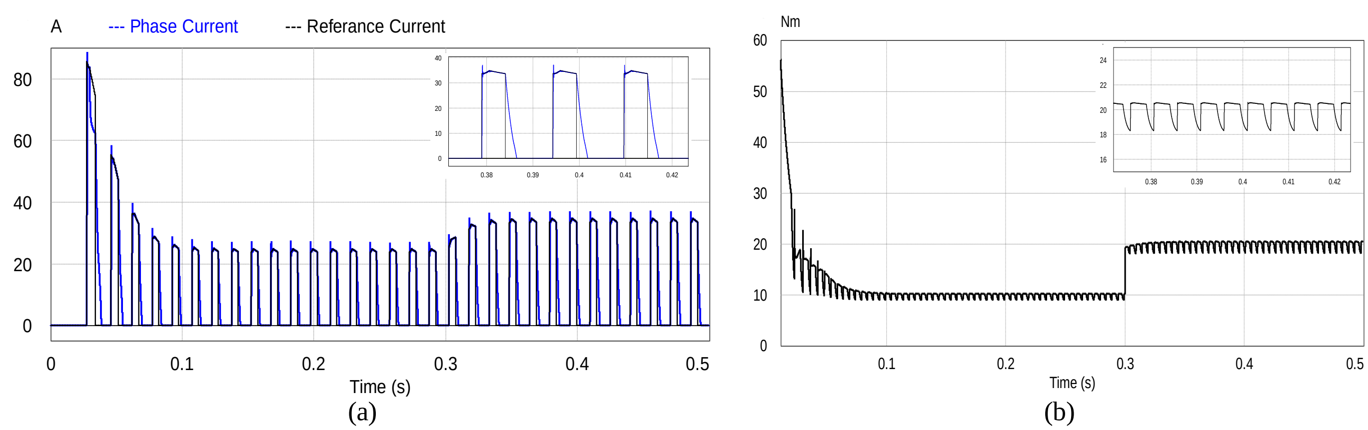


Fig. 11. *The SRM performance with FLC (a) Phase current, (b) Motor torque.*

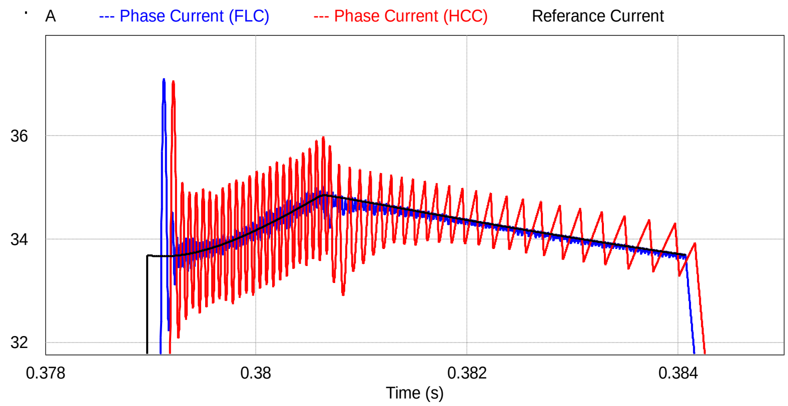
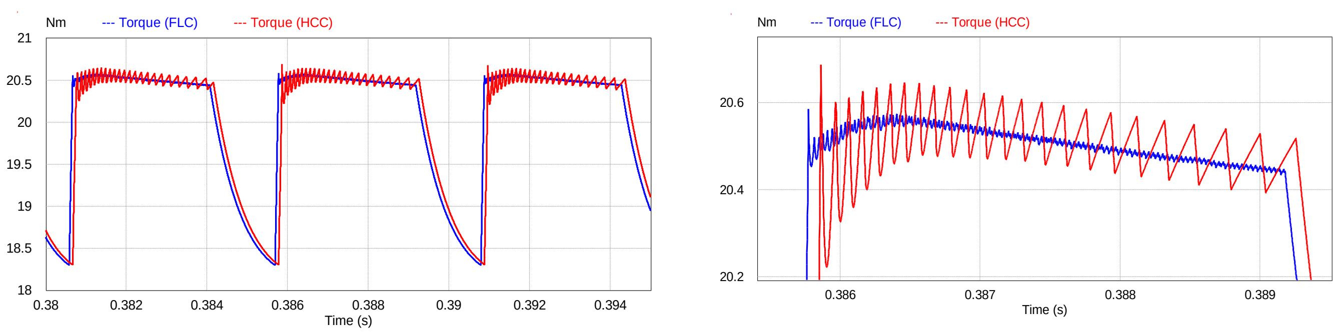


Fig. 12. *SRM phase current response with FLC and HCC*

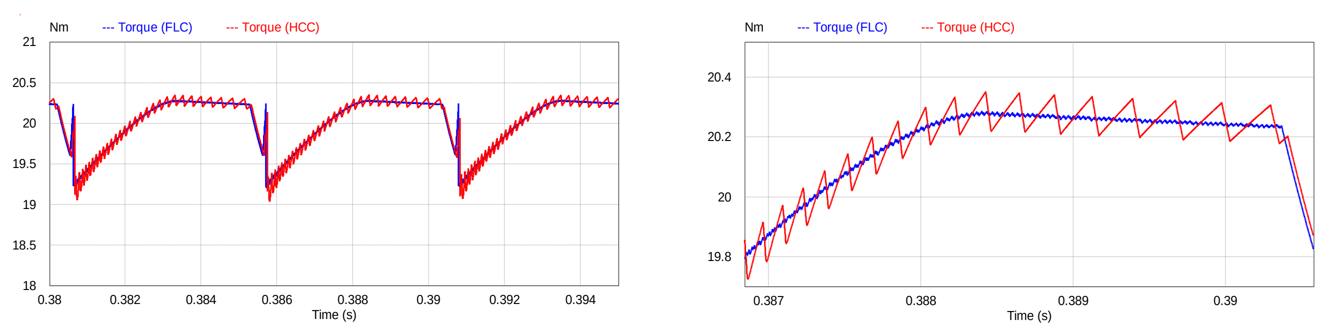
As a result of current ripples reduction in case of FLC, the torque ripples during phases conduction period have been reduced as shown in Fig. 13(a, b). In Fig. 13(b), the red color represents SRM torque using HCC, and this torque in the blue color in case of FLC. The torque ripples during phase conduction period in FLC smaller than in HCC. Of course, the SRM torque ripples still needed to be minimized particularly in phase commutation period, this period wasn't depending to the current controller, but depend to the optimal turn on and turn off angle according to motor parameters, so that the proposed current controller is tested with two different turn on angle to investigate the effectiveness of this methods.

The simulation result of motor torque in case of θ_{ON}=115° shown in Fig. 14. Actually, the change of the turn on angle have no noticed effect on phases current, because of each phase have independent controller, but it is clear that when the turn on angle changed, it directly affects motor torque profile but still the torque ripples by using FLC small than the ripples with HCC as shown in Fig. 14(b).



(a) (b)

Fig. 13. *SRM torque with θ_{ON}=100° (b) Zoom during one conduction period.*



(a) (b)

Fig. 14. *(a) SRM torque with θ_{ON}=115° (b) Zoom during one conduction period.*

The previous results show that, the proposed current control technique have many benefits comparing with traditional technique not only because of their constant switching frequency but also it makes the phases current tracked the reference current signal with a small value of current ripples (ΔI) as concluded in Table 3. Because of the phase current effect directly on motor torque, the motor torque ripples also can be reduced by using the fuzzy logic current control.

6. CONCLUSIONS

In this paper, fuzzy logic current controller of switched reluctance motor drives for electric vehicles applications was introduced. This controller is programmed by C- code and the simulation test performed with 60 KW SRM. By adopting the FLC, the SRM current track the reference signal with minimum values of current ripples comparing with traditional current control techniques, and hence, the torque ripples during the conduction period of each phase of the motor were reduced. The controller was tested at different load conditions and with different turn on angles. The obtained simulation results show the effectiveness of the FLC method to reduce the SRM current and torque ripples.

Table 3: SRM phases maximum current ripples (HCC vs FLC)

$\Delta I_{Max} \approx$ / SRM Phases	$\theta_{ON}=100°$		$\theta_{ON}=115°$	
	HCC	***FLC***	***HCC***	***FLC***
Phase a	9 %	2%	9.4%	2.2%
Phase b	9.3%	2.5%	9.7%	2.8%
Phase c	9.9%	2.7%	10.2%	3.1%

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