A New Phase Current Profiling with FLC for Torque Optimization of 12/8 SRM

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ABSTRACT

The switched reluctance machine against its several merits such as simplicity, robustness, less cost manufacturing and large speed still suffers from its undesirable torque ripple and acoustic noise. Compared to different candidates of hybrid and electric vehicle engine, the frequency of use of SRM in traction drives is improved with the different optimizing torque oscillation solutions. Most of studies used the generic or specific model of switched reluctance machine in the Simulink library (6/4,8/6 and 10/8). Despite, a new non linear model simply implemented in Simulink tool using a static finite element analysis a previous study is used in this work. Hence, a 12/8 non linear SRM drive system is simulated using MATLAB toolbox tested with an intelligent controller (FLC) in order to minimize the torque ripple of an oriented starter –alternator application of a hybrid vehicle.

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1. INTRODUCTION

The Switched Reluctance machines have undergone a fast improvement in traction trains of hybrid electric vehicles indeed with the appearance of the starter-alternator systems along the past two decades. As a matter of fact, with its salient structure for both the stator and the rotor the SR motor with the absence of permanent magnets can be suitable for harsh mainly dealing with excellent performances in high temperatures [1]. Despite, the acoustic noise still one of the major problems in SRMs which is caused by the radial forces that increase inversely with the air gap and especially when the force frequency is near the stator resonant frequency .Several issues aimed to analyze SRM design and predicting its dynamic behavior in order to attend the best performances. The nonlinearity of switched machine makes very difficult the modeling of the flux linkage or the inductance. Many researchers have been investigated in dynamic modeling of the switched reluctance machine based on its non linear characteristics $\lambda(\theta,i), T(\theta,i) and\ L(\theta,i)$generated from Finite Element Analysis such as Parretra in 2005, Chang in 2007 and Sahoo in 2012.Besides the geometric configurations studied have been usually the 6/4 and 8/6 models.

With neither winding nor magnet on the rotor, the torque of SRM is produced with a reluctance variation among the magnetic circuit: when each stator windings are excited independently with voltage or current so that each pole tries to attract the closest rotor pole toward the alignment of the poles. Thus, the inductance produced of each phase is maximum at its aligned position because the magnetic reluctance is the lowest at that position and minimum at unaligned position for the highest reluctance. Consequently the highest torque oscillations are obtained during the commutation form a phase to the next one during the torque production as presented in Figure 1. This high torque disturbance stimulates the acoustic oscillations which seem to be more and more severe compared to the other traditional motors. As a matter of fact, different techniques have been developed to minimize that ripple even through control skills or with a suitable choice of power electronic converters. Many attempts have focused on newly techniques to decrease the amount of ripple in generated torque like in [2] and [3] using a Neuro-Fuzzy compensation of the torque ripple. Moreover, other recent researchers have oriented their studies toward the Fuzzy-Locgic control of the SRM drive as a solution for less ripple generated such as Uma.J and Jeevandham A in [4] and Thankachan N, Reeba S in [5] within a detailed discussion have been introduced a dynamic non-linear model of 8/6 switched reluctance machine designed for drive applications.

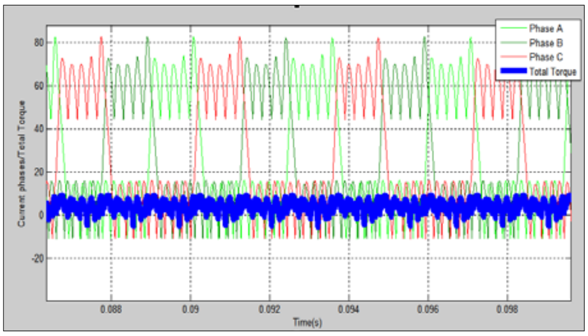


Figure 1. Variation of measured current and corresponding ripple total torque

In fact, Several techniques as summarized in Figure 2. aiming to reduce the torque ripple of a switched reluctance machine have been published in literature [6]. They are divided into two themes: the first one includes the motor geometry modification and the second one discusses the current control techniques.

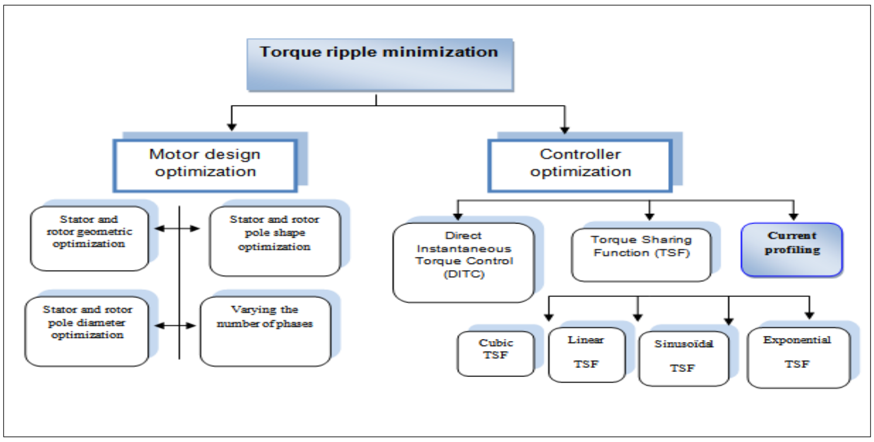


Figure 2. Torque ripple optimization techniques

The SRM geometry can be optimized by modifying stator and rotor's diameters or there pole shapes. Moreover the number of phases can be reduced in such cases as in [7]. Previous studies have primarily concentrated in 6/4 and 8/6 models presented as generic and specific models in the MATLAB-Simulink library. However, to the best of author knowledge, no report has been found so far using a FEMM study of 12/8 SRM model coupling MATLAB. As a matter of fact a FEA study have been previously made to build a 2-D model for the starter alternator of a micro-hybrid vehicle using static data for dynamic testing behavior. The torque ripple as a noisy factor in drive application has been the aimed search of many issues. For that reason, we discuss next all these optimization strategies used for the torque ripple minimization but we put a spotlight next in the current profiling technique which previously used for an open-loop control dynamic model as described next .Besides, the current study has presented a new closed-loop control for the 12/8 SRM drive chosen configuration.

2. TORQUE RIPPLE OPTIMIZATION

2.1. Origin of torque oscillations

The most important causes of torque oscillations are the consecutive excitations (voltage or current). Thus, The air gap which is directly related to the generation of electromagnetic torque with the equation (1):

$$V = Ri + \frac{d\Psi}{dt} \tag{1}$$

$$\psi(\theta, i) = \int (V - Ri)dt \tag{2}$$

Where:

- V: the voltage measured in one phase
- Ψ or λ(i,θ) : the magnetic flux in linear model is given by :

$$\lambda(i, \theta) = L(i, \theta) * i \tag{3}$$

L (i,θ) : the phase inductance

As a matter of fact, the non-linearity of flux and so the discrete torque generation mechanism increase the reasons for high ripple in the torque as described in Figure 3. The instantaneous torque represented in Figure 4 below is the sum of all the single torque produced from each phase excited independently [8].

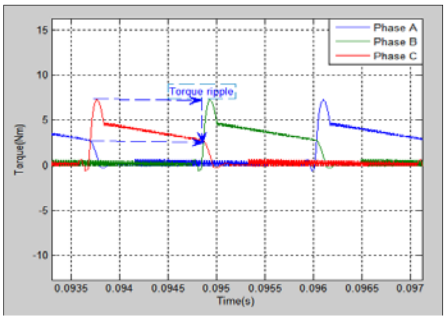


Figure 3. Torque ripple

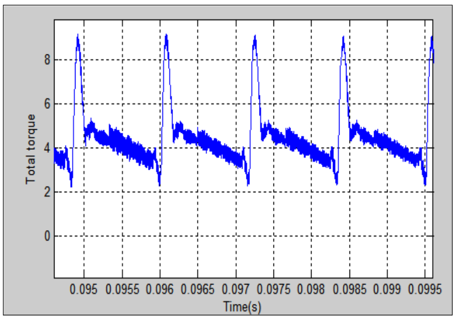


Figure 4. Instantaneous total torque

Torque ripple percentage, is defined as the difference between the maximum and minimum instantaneous torque of the average torque during steady state operation. Analytically, this percentage is given next in equation (4):

$$T_{ripple} = \frac{T_{\max} - T_{\min}}{T_{av}} \%100 \tag{4}$$

The optimization of torque ripple [9] seems to be primitive in applications enforcing high performances thus the obligation of involving a smooth operation with the smallest torque pulsations. Accordingly, machine designers have focused on changing the stator and rotor pole structures in order to reduce the torque pulsations but as a result it can lead to increase the motor expense. Moreover, the development of electronic approaches in, 2002 with HUSAIN EHSANI, was joined with a selective studies for combination of the operating parameters such as the choices of turn on and turn off angles, the supply voltage, the current level. Additionally, INANC OZBULUR in 2003 had presented a simple current modulation procedure is widely used for the minimization of torque ripples in SRM. Ultimately, the methodology discussed in this paper is based on controller optimization techniques.

3. CURRENT COMPENSATION STRATEGY

The Current Profiling strategy explained in [10] is based on phase current reshape which is the major cause of to torque ripple. This technique requires the knowledge of the non-linear magnetic characteristics of the SRM T (i,θ) as discussed previously. According to the past studies as D. Schramm, B.

Williams, and T. Green in 1993 and Iqbal Husain, Mehrdad Ehsani in 1996, it is possible to optimize the overlapping current during the commutation and then through recognizing a central point where the next incoming and outputting phases could be equal.

3.1. SRM static model

The electrical equations governing the SRM behavior are cited in (1), (2) and (3). Moreover, the flux characteristic has been calculated using a 2D finite element magnetic method with FEMM with varying the rotor position from (0° to 45) with a step of 0.5° in order to fulfill the motoring and generating mode (see Figure 7). In order to realize the non linear model explained next we need to use the inversion of the characteristic (see Figure 5). After a cubic, spline or polynomial interpolation, the flux linkage inverse resulted is called i(Ψ,ɵ) as represented in Figure 6.

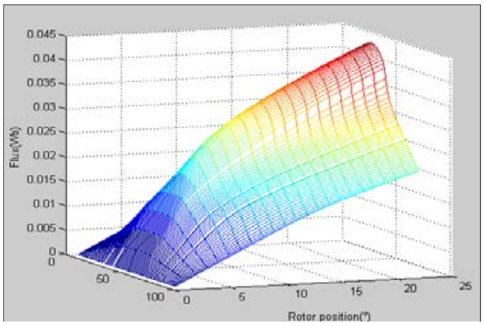


Figure 5. A 3D magnetic flux linkage

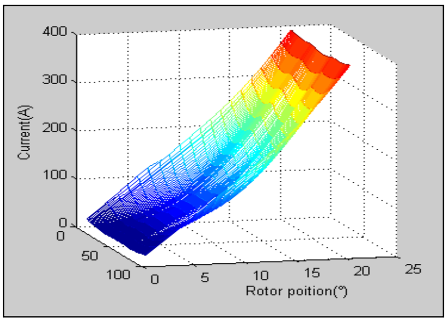


Figure 6. The i (Ψ,ɵ) characteristic (3D)

3.2. The compensation procedure

The basic principles of the compensation theory have been discussed in different issues as in [11] and [12]. Actually, the SRM driving system as shown in Figure 7 is running in a speed control mode.

The Figure 9 shows, the scheme block of the proposed compensation theory. Eventually, the output signal named Δicom is added to the input of the classic controller PI in order to regulate the signal command causing the ripple and in that case is the current. The regulated signal can be a function as described below in relation (5) of a rotor position, the torque load, the speed and the phase current. Subsequently, Δi_{com} is then injected in the SRM driving system [13].

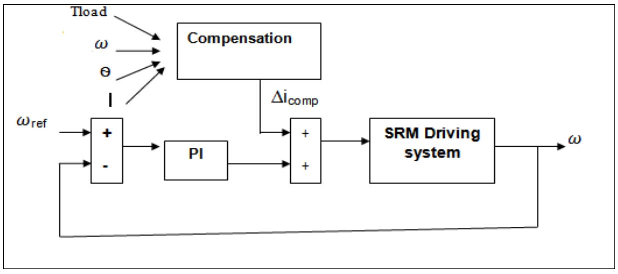


Figure 7. Block scheme of compensation strategy

$$\Delta i_{com} = f(\theta, \omega, T_{load}, i) \quad (5)$$

As mentioned in (5) the compensator is a function of inherent variable. Hence, in order reduce the complexity of resolution, the we can decrease these variable into only two ɵ the rotor position and the output current coming from the PI speed controller. The (5) will be written then as given next:

$$\Delta i_{com} = f(\theta, i_{PI}) \quad (6)$$

3.3. Intelligent fuzzy controller

In recent studies, the intelligent controllers as the fuzzy logic controller (FLC) and the adaptive Fuzzy neuro-fuzzy inference system are designed for nonlinear control. Therefore, fitting the discrete SRM model, is appropriate to use both or one of them to reduce the torque ripple. Hence, the FLC is easy to implement because it estimates relations between chosen variable despite their analytical dependency. Consequently, the current compensated called I_{comp} which is the result of I_{ph} the phase current of SRM drive system described previously so then I_{ref} the output of the speed controller can be injected in each phase using FLC output estimated from its nominal membership functions chosen according to the parameters of the dynamic motor behavior.

The fuzzy control of SRM using FLC or also named Mamdani controller, utilizes as input the rotor position θ and the current coming from the speed controller (generally a PI is used) and then produces the compensating current as the output. The integration of FLC in block scheme of speed control is given next in Figure 8.

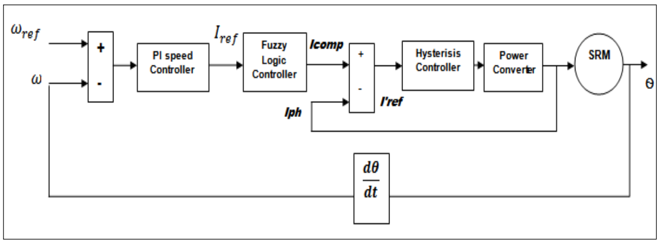


Figure 8. Block SRM drive scheme with controller

4. SIMULATION RESULTS AND DISCUSSION

The non-linear 12/8 SRM model is represented in Figure 9. The static characteristic was estimated using the Finite Element Method Magnetics (FEMM) software. The SRM is fed in this simulation using the asymmetrical power converter in which, each leg consists of two IGBTs and two freewheeling diodes. Thus, the phase currents are independently controlled by an hysteresis current controller which engender the IGBTs drive signals by comparing the measured currents with the references. The IGBTs switching frequency is determined using the hysteresis band for a previous optimal study fixed at ΔI =+-0.1A. The firing angles: turn-on and turn-off angles are kept constant at 22.5deg and 37 deg. A PI classic controller is used to regulate the speed. For a K_i= 0.25 and K_p= 1.25 fixed yet, the fuzzy controller's membership functions are limited with these values of current, the rotor position and the limit of current compensation.

The non-linear SRM dynamic closed-loop speed controlled at no load is shown in Figure 10. Noticeably, the rate of error or the current reference as the output of PI controller with the rotor position is inserted in the fuzzy logical controller as inputs. During the fuzzification they became a fuzzy variables. Subsequently, the output I_{comp} is added to the reference current and then compared with the instantaneous SRM current.

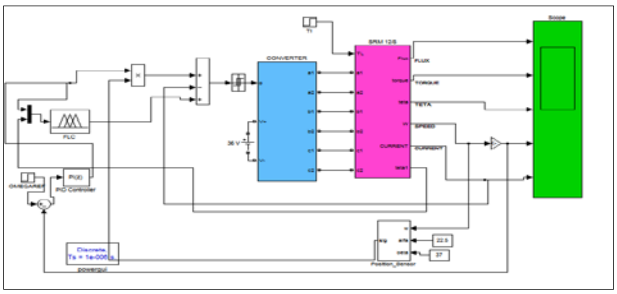


Figure .9 the closed speed control of non linear SRM with FLC control

In Figure 10, the static characteristic of torque is divided into 7 regions in function of torque behavior. Thus, the FLC tends in regions when the torque is increasing or decreasing in A,B,F and G to reduce as output the ripple by the addition of current compensation where we use the fuzzy rules of output Icomp the PVB and PVVB .Hence, in the regions where the torque increase slowly in D and E we introduce the rules PM and PS to inject slowly the current I_{comp}.

As known, the torque ripple is basically the reason of acoustic noise creation. As a result, torque ripple optimization decrease mechanical stress [12]. In this study, the magnetic characteristic T(i,ɵ) divided in seven regions in Figure 10. Hence, the torque in regions D seems to be the almost constant (see Table 1) despite the other ones where the interaction of FLC is needed to regulate with current compensation the torque ripple.

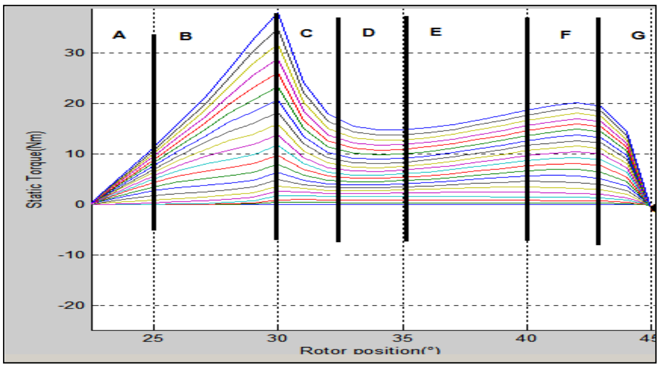
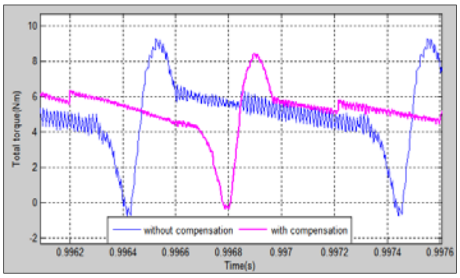


Figure 10. Non linear magnetic characteristic T(i,ɵ)

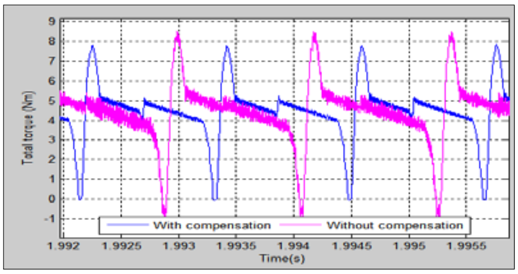
Table 1. The non-linear regions of static torque characteristic

Region	Rotor position(°)
A	$22.5 \leq \theta \leq 25$
B	$25 \leq \theta \leq 30$
C	$30 \leq \theta \leq 32.5$
D	$32.5 \leq \theta \leq 35$
E	$35 \leq \theta \leq 40$
F	$40 \leq \theta \leq 43$
G	$43 \leq \theta \leq 45$

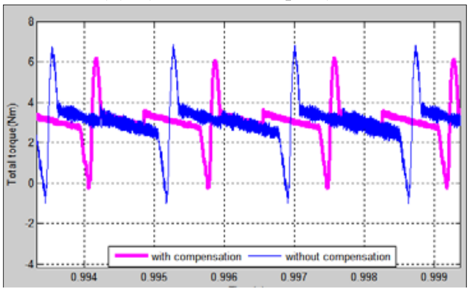
The simulation was carried out into two parts. First, the SRM drive system is simulated for a speed reference without the compensation. Then the current is estimated in nominal speed (2160rpm). As a matter of fact. According to Figure 11 (a, b, c, d) illustrating the total torque with and without FLC for different speeds (500,1500,2160,2500) rpm , the current compensation strategy imposed through the FLC has reduced the ripple with a percentage between 30% and 15% under the initial simulation. Besides, the Figure 12 shows also a drop up of current value with the presence of pulses as effect of the new added current coming from the FLC, which improve the i of torque oscillation optimization.



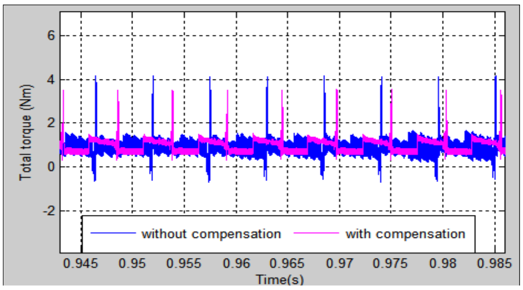
(a) $(\boldsymbol{\omega = 2500rpm})$



(b) $(\boldsymbol{\omega = 2160rpm})$

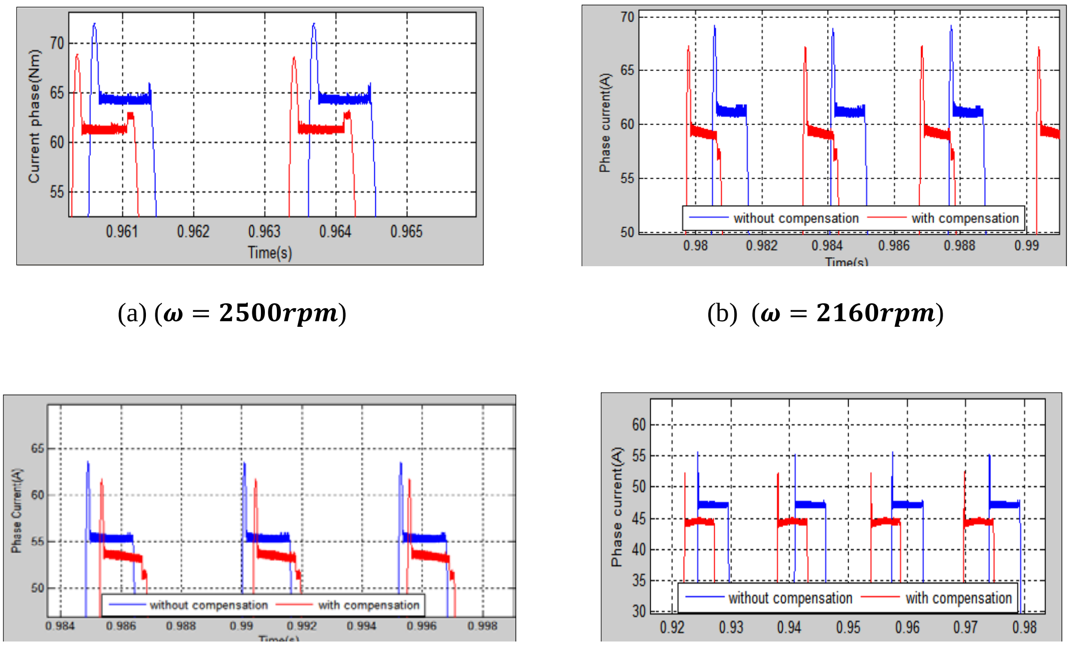


(c) $(\boldsymbol{\omega = 1500rpm})$



(d) $(\boldsymbol{\omega = 500rpm})$

Figure 11. The total torque with and without compensation



(a) ($\boldsymbol{\omega = 2500rpm}$) (b) ($\boldsymbol{\omega = 2160rpm}$)

(c) ($\boldsymbol{\omega = 1500rpm}$) (d) ($\omega = 500rpm$)

Figure 12. The phase current with and without FLC

4. CONCLUSION

In this paper we have developed a new compensation device using a fuzzy logical controller with speed closed-loop control of a non linear 12/8 SRM drive. In this projected method, the non linear magnetic torque characteristics was the keys to build FLC membership and estimate the torque variation with rotor position to optimize the torque ripple which become one of the major subject of developed current studies. Therefore in this paper, the new strategy based on current compensation was applied to estimate the dynamic response of a 12/8 SRM discrete prototype used as a starter alternator of hybrid vehicle with a nominal speed of 2160 rpm. The Dc voltage estimated of batteries is about V=36V.. Using the static characteristics from a finite element magnetic method essays, the tested dynamic model with the proposed new strategy of current compensation has improved with the FLC a better robust control action compared with conventional PI controller with less percentage of torque ripple.

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A native of Kairouan, born in 1984 in Monastir, Tunisia. She had the B.Sc. degree in electrical engineering from Ecole Nationale d'Ingénieurs de Sfax-Tunisia (ENIS) , in 2008, the M.Sc. degree in electrical engineering (Renewable energy) from the same school (ENIS), in 2011. She joined the Laboratory of Electronics and Information Technology (LETI), Electric Vehicle and Power Electronics Group (VEEP)in 2011.She is currently a PhD student and a technologist in Superior Institute of Technologies in Kairouan, Tunisia.Since 2010, she has been a member of the Laboratory of Electronics and Information Technology (LETI), Electric Vehicle and Power Electronics Group (VEEP). Her main research interests include analysis, design, and control of electric machines for EV applications.

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