Mehmet Aytac CINAR[1], Feriha ERFAN KUYUMCU[2]

University of Kocaeli

Design and Torque Profile Analysis of an Outer-rotor SR Motor with Different Winding Configurations

Abstract. *This paper presents an outer rotor in-wheel switched reluctance motor, designed for a cart type electric vehicle. Both of the short and fully pitched winding configurations are developed and analyzed considering the requirements of such a vehicle propulsion motor. Torque profiles and ripple ratios, which are the most important parameters of in-wheel applications are compared for various loading conditions. It is observed that with fully pitched configuration, torque output is increased. However, increasing ripple ratio makes this winding configuration inconvenient for in-wheel propulsion applications, unless any ripple control algorithm is applied.*

Streszczenie. *W artykule zaprezentowano przełączalny silnik reluktancyjny zaprojektowany do pojazdów elektrycznych. Zaprojektowano odpowiednią konfigurację uzwojeń uwzględniając wymagania pojazdu. Głównym wymaganiem był moment napędowy i pulsacje momentu. (**Projekt i analiza momentu silnika reluktancyjnego umieszczonego na kole pojazdu**)*

Keywords: outer-rotor switched reluctance motor, winding configuration, torque analysis, torque ripple.
Słowa kluczowe: silnik reluktancyjny, moment napędowy, uzwojenia.

Introduction

Increasing number of internal combustion engine powered vehicles continues to cause various economical and environmental problems. These problems have forced researchers to consider alternative energy resources and vehicle concepts. Electrical energy is a well suited choice for vehicle propulsion.

Among various single motor and multi motor drivetrain systems, proposed in literature, in-wheel type multi motor systems are the most reliable and efficient propulsion topologies. This topology is not only highly applicable for pure electric vehicles, but also series hybrid and fuel cell vehicles, as described by [1]. In this topology, torque, delivered to individual wheels, can be precisely controlled by propelling each wheel with a seperate motor. Each propulsion motor could be either classical inner rotor type or unconventional outer rotor type constructed.

As explained by [2,3,4], robustness, high efficiency and competitive cost are required features for an in-wheel motor. In addition, it should be able to produce high torque and operate in wide speed range. Considering this requirements, switched reluctance (SR) motors seem to be the remarkable choices similar of the permanent magnet motors. Nowadays, continuing researches on in-wheel SR motor applications are focused on performance improvements by novel and optimized magnetic designs such as axial flux magnetic circuits and applying modern control methods to the motor controllers, as given by [5,6,7,8,9].

In this study, an outer rotor type in-wheel SR motor which has conventional radial flux magnetic circuit and short pitched winding configuration, is designed and realized for a cart type electric vehicle. In motor design process, electromagnetic field analyses are carried out by finite element analysis (FEA) software. Dynamic behaviors under various operating conditions are studied and applicability to an electric vehicle is investigated. Then, fully pitched winding configuration, which was firstly described in [10], is applied to the designed in-wheel motor. Torque production capabilities and torque ripple ratios of these winding configurations are compared and pros and cons are evaluated.

Design limitations

In the design process of such a propulsion motor, several mechanic and electromagnetic limitations should be taken into consideration.

An outer rotor in-wheel motor is designed to place into the wheel rim of an electric vehicle. In motor design process, rim dimensions are the limit values of the outer rotor outer diameter and the in-wheel motor length. Dimensions of a widely preferred wheel rim of a cart type electric vehicle are 8x7 inches. That means, the diameter is 8 inches (=203,2mm) and the depth is 7 inches (=177,8mm) of the rim.

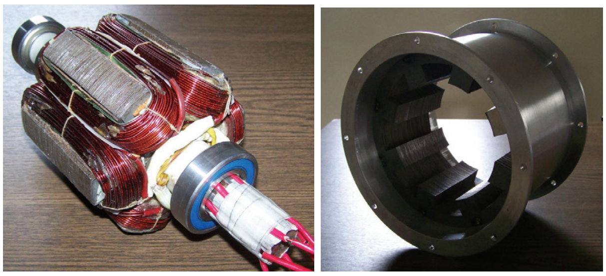
Due to the SR machine is designed to operate intensively on into saturation zone, B-H characteristic of the magnetic material is also important. In electromagnetic design process, electromagnetic parameters, obtained from B-H curve, greatly affect of pole angles, stator tooth height and rotor yoke width. In this study, in order to reach high magnetic induction level, lamination material of inner stator and outer rotor is preferred as M19 non-oriented electrical steel.

Produced torque value and motor speed are quite important parameters for in-wheel traction motors. In in-wheel topology, due to the lack of any gears with different reduction ratios, these parameters directly correspond to the wheel torque and wheel speed of the vehicle. So, design optimization process has great importance to obtain satisfying torque profile and speed.

In addition, due to the torque ripple is the characteristic problem of switched reluctance topology, ripple value should be taken into consideration in such an application, as well as rated torque value. To obtain higher driving comfort and mechanical strength of moving parts of drivetrain, smoother torque waveform is preferred in electric vehicles. So, selection of the numbers and angles of stator and rotor poles are other important criterias to optimize in design process. With higher pole numbers, ripple in torque waveform decreases while its mean value is increasing. However, the area of one stator pole and phase winding decrease, due to geometrical constraints. Because of that, different winding configurations and their affects on torque value and ripple are studied in this study.

Motor construction

Designed SR motor is a doubly salient and single excited machine. Both the inner stator and outer rotor consist of stacks of non-oriented steel laminations. Only the inner stator has excitable copper windings. The outer rotor has no phase windings or permanent magnet materials, as shown in Fig. 1.



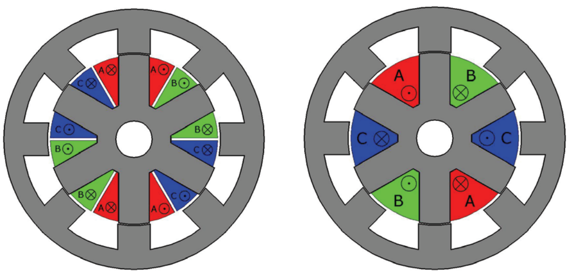
(a) (b)

Fig.1. (a) Inner stator, (b) outer rotor of the in-wheel SR motor

Two different winding configurations, given in Fig. 2., are applied for the designed motor, to improve the torque profile. For both configurations, dimensions of the stator and rotor cores and the air gap length are kept constant.

In conventional SR motor winding configuration, which is called short pitched configuration, shown in Fig. 2a., windings on diametrically opposite inner stator poles are connected in series and constituted one phase of the motor. When the phases are excited in sequence, the rotor poles in the vicinity are sworn into the field of the excited phase, thus producing continuous rotation of the rotor.

In fully pitched winding configuration, shown in Fig. 2b., each phase is wound around a number of stator teeth equal to the number of phases, so that each winding spans one complete magnetic pole.



(a) (b)

Fig.2. Cross sections of designed, (a) short pitched, (b) fully pitched, wound in-wheel SR motor

The number of turns per phase and winding cross-sectional area are kept identical for both winding configurations. However, because of the increased end winding length, total phase resistance is increased, resulted from the increase of total length of the phase winding.

Torque production capability

When the phase winding is energized, magnetic co-energy can be calculated on the basis of the flux linkage as,

$$W_{co}(\theta,i) = \int_0^i \lambda(\theta,i)di\Big|_{\theta=const} \tag{1}$$

General instantaneous torque produced by a phase is calculated from co-energy as,

$$T_{ph}(\theta,i) = \frac{\partial W_{co}(\theta,i)}{\partial \theta}\Bigg|_{i=const} \tag{2}$$

Total instantaneous torque of the SR motor is given by the sum of the torque values of each phase as,

$$T_i(\theta,i) = \sum_{phases} T_{ph}(\theta,i) \tag{3}$$

The average torque of the SR motor is derived from the instantaneous torque is given by,

$$T_{av} = \frac{1}{T}\int_0^T T_i dt \tag{4}$$

Torque ripple is defined as, the difference between the maximum and minimum instantaneous torque expressed as a percentage of the average torque during steady state operation,

$$\%Ripple = \frac{T_i(\max) - T_i(\min)}{T_{av}} \tag{5}$$

Magnetic saturation and current dips are the main reasons of the ripple on the torque profiles. Below rated current value, current dips, during phase commutation instants, are the greatest reason of the ripples. Additionally, above rated current, saturation effect causes to increase the torque ripple ratio.

General expression of electromagnetic torque for a three phase SR motor is given as follows,

$$T = \frac{1}{2}i_a^2\frac{dL_a}{d\theta} + \frac{1}{2}i_b^2\frac{dL_b}{d\theta} + \frac{1}{2}i_c^2\frac{dL_c}{d\theta} + i_a i_b\frac{dM_{ab}}{d\theta} + i_b i_c\frac{dM_{bc}}{d\theta} + i_a i_c\frac{dM_{ac}}{d\theta} \tag{6}$$

In a short pitched wound SR motor, the coupling between phases is negligible. Therefore, torque is produced from changes in self inductance with rotor position. However, in a fully pitched wound SR motor, excited windings at the same period have a mutual inductance. The mutual inductance is a function of rotor position, whilst the self inductance values remain almost constant. In this winding configuration, the majority of torque is produced from changes in mutual inductance with rotor position. In operation, at least two of the three phases simultaneously contribute to torque production. In a typical industrial frame, 20-30% more torque can be produced.

Operation with conventional winding configuration

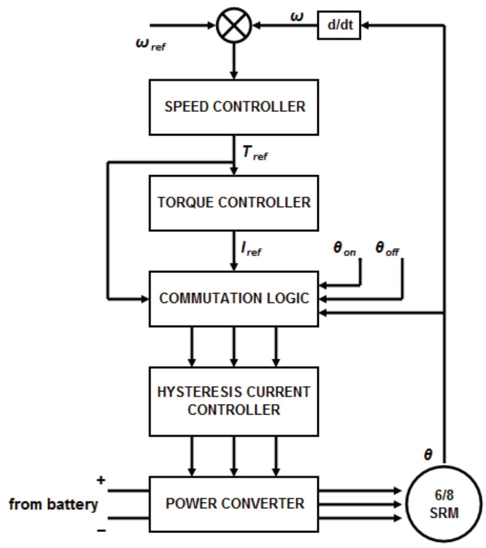
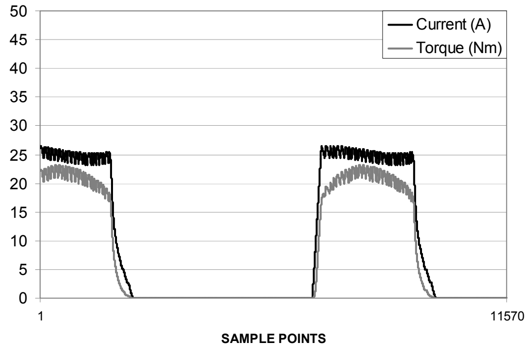


Fig.3. Schematic of the closed loop drive system

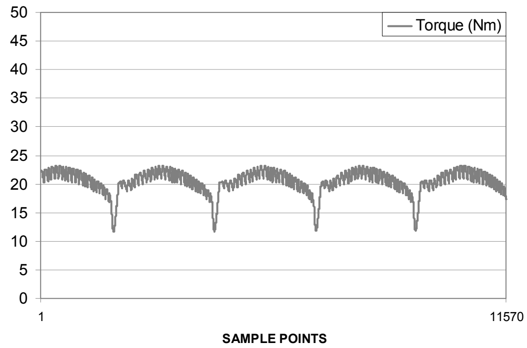
The schematic of the closed loop drive system is shown in Fig. 3.

An asymmetric converter topology, consists two power switched and two diodes per phase, has been studied to control the phase supply. Structural simplicity and controllability of each phase independently of the other phase windings are the main advantage of this topology. Fixed angle control method has been applied to the driver. In this method, controlled switches of each phase are turned on at an electrical angle θ_{on} and turned off at θ_{off} to keep the conduction angle constant. Reference current value, defined by torque controller, are compared with the phase currents in the current controller. The current controller then decides the switching instants of the corresponding phase switches. Hysteresis control is used for current stabilization at low speeds.

Different speed operations taking into account different loading conditions have been studied. These operations correspond to various driving conditions of the vehicle. Steady state waveforms of phase variables and produced electromagnetic torque are shown in Fig. 4-5. All waveforms given in these figures contain 11570 samples in a time period of 0,1 s.



(a)



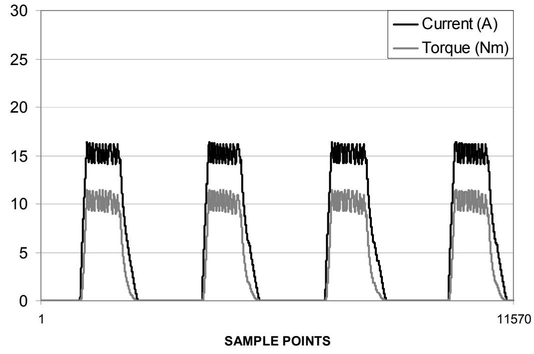
(b)

Fig.4. Steady state waveforms of 20Nm, 143rpm condition, (a) phase variables, (b) total electromagnetic torque

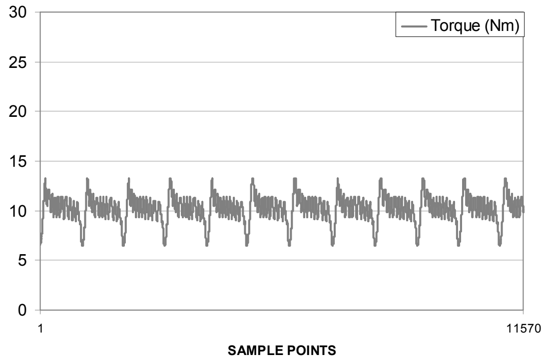
Fig. 4. shows the results for 20Nm and 143 rpm speed range. This load condition corresponds to the driving conditions such as starting, traveling at heavy load or climbing hills. The ability of producing high torque of the motor is quite important for these conditions. Total average torque of about 80Nm, appears completely sufficient for a four-wheel propelled cart type vehicle.

Fig. 5. shows the result for 10Nm and 296rpm speed range. This operation corresponds to the driving condition, such as traveling at light load.

High torque ripple is the main drawback of SR motor topology. Ripple ratio is calculated as 32,76% for 20Nm loading condition. This value seems to be high. However, in in-wheel motor applications, the rated torque of the machine is only required at low speeds, whereas a reduced torque is generally needed at the maximum speed of the vehicle. In addition, inertia of the vehicle would make a flywheel effect and render this problem partially. For this condition, torque ripple is calculated as 14,2%. This value is quite low and would not make any problem for the performance of the motor.



(a)



(b)

Fig.5. Steady state waveforms of 10Nm, 296rpm condition, (a) phase variables, (b) total electromagnetic torque

Torque analyses of winding topologies

Because of the increasing winding length and phase resistance, it is not possible to compare short pitched and fully pitched winding configurations for the same current values. This comparison is only possible for either equal winding losses or the same magnetic operating point. For constant magnetic dimensions, these two condition could not been obtained at the same time. In this study, torque profiles and ripple ratios of different winding configurations are compared using the basis of equal winding losses, as described by [10].

For short pitched and fully pitched wound SR motors, winding loss equations per phase are given as,

$$P_{ph} = \frac{1}{3} i_{sp}^2 R_{sp} \tag{7}$$

$$P_{ph} = \frac{2}{3} i_{fp}^2 R_{fp} \tag{8}$$

where i_{sp} and i_{fp} are the phase currents of short pitched and fully pitched winding phase currents, respectively.

Because of the increased end winding length, total phase resistance is increased by 41,87%, resulted from the increase of total length of the phase winding. Equating (7) with (8) and substituting the phase resistance values, phase current value of fully pitched wound SR motor for equal winding loss is obtained as,

$$i_{fp} = 0{,}518 i_{sp} \tag{9}$$

For a cart type vehicle, there will be no need to reach the higher speed values more than the rated value. Designed in-wheel motor operates in its normal mode of operation interval up to its rated speed. At this speed, the motor reaches its rated power limit. Considering the driving cycle of a cart type vehicle, it is decided that, an in-wheel electric propulsion motor operates among 50% and 100% of its rated power. In other words, phase current will be charged in a driving cycle continuously. Therefore, in this study, different current values would be investigated for both winding configurations.

In Fig. 6., a comparison of static torque profiles of short pitched and fully pitched wound SR motors are given. This torque waveforms are obtained for a current of 25A, which is the rated current value of the short pitched wound motor, and corresponding current value of the fully pitched wound motor under equal winding loss.

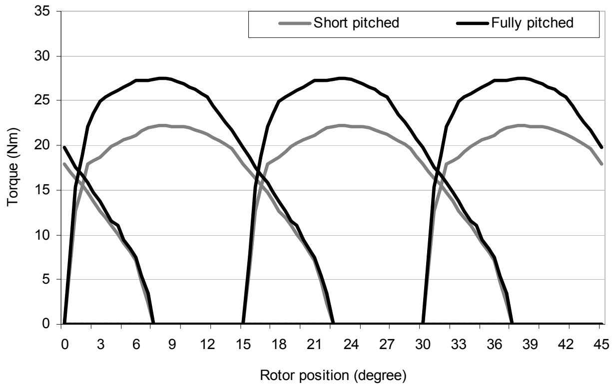


Fig.6. Comparison of static torque profiles of winding configurations (i_{sp}=25A, i_{fp}=14,84A)

Average torque values, change in torque and calculated ripple ratios of both winding configurations for different current levels are given in Table 1 and Table 2.

Table 1. Average torque values for both winding configurations of outer rotor SR motor

Short pitched wound SR motor		Fully pitched wound SR motor		Change %
Current (A)	Torque (Nm)	Corresponding Current (A)	Torque (Nm)	
5	1,342	2,97	2,036	+51,71
10	5,030	5,94	6,767	+34,53
15	9,521	8,90	12,900	+35,49
20	14,655	11,87	19,650	+34,08
25	19,885	14,84	24,387	+22,65

As shown in Table 2, short pitched wound SR motor generates an average torque of 19,885Nm, at rated current. In this condition, torque ripple is calculated as 32,76%.

Table 2. Ripple ratios for both winding configurations of outer rotor SR motor

Short pitched wound SR motor		Fully pitched wound SR motor	
Current (A)	Ripple ratio %	Corresponding Current (A)	Ripple ratio %
5	5,88	2,97	5,47
10	9,25	5,94	8,08
15	14,04	8,90	21,08
20	21,60	11,87	31,66
25	32,76	14,84	42,78

As known, high torque ripple is the main drawback of SR motor topology. This value is also similar to conventional SR motors. However, it is thought that, inertia of the vehicle would make a flywheel effect and render this problem partially. Below rated current, which correspond to the driving conditions such as traveling at light load, ripple ratios decrease, depending upon the decreasing magnetic saturation and average value of produced electromagnetic torque.

Fully pitched winding configuration leads to an increase in average torque per unit winding loss of between about 23% and 52%, depending upon load condition in the new machine. This improvement provides a great advantage to a vehicle propulsion motor. However, this increase also causes higher ripple ratios between 30% and 50%, in common operation interval of the motor.

Conclusion

In this study, a radial flux type outer rotor in-wheel switched reluctance motor is designed for electric vehicle propulsion. Torque production capability and torque ripple, which are the most critical issues of an in-wheel propulsion motor, are considered in the design process. Both short and fully pitched winding configurations are applied for this propulsion motor.

Such a motor operates at continuously varying conditions in a driving cycle of the vehicle. Torque profiles for both winding configurations are analyzed for these conditions. Results show that, at low currents, fully pitched wound motor produces higher torque and has lower ripple. However, while the current is coming closer to the rated value, torque ripple rapidly increases.

As a result, designed outer rotor in-wheel switched reluctance motor appears to be a viable choice as a propulsion motor for cart type vehicles. However, unless this ripple minimized by using modern control methods, fully pitched winding configuration would not be suitable for such an application.

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***Authors**: asst. prof. dr Mehmet Aytac Cinar, University of Kocaeli, Izmit Vocational School, Arslanbey Yerleskesi, 41285, Kocaeli, Turkey, E-mail: aytac@kocaeli.edu.tr; prof. dr Feriha Erfan Kuyumcu, University of Kocaeli, Dept. of Electrical Engineering, Umuttepe Yerleskesi, 41380, Kocaeli, Turkey, E-mail: erfan@kocaeli.edu.tr*

The correspondence address is:e-mail: aytac@kocaeli.edu.tr