Piotr MYNAREK, Rafał GABOR, Marcin KOWOL, Janusz KOŁODZIEJ, Marian ŁUKANISZYN

Opole University of Technology

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Analysis of a Modified-Structure Switched Reluctance Motor Designed for an E-Bike

***Abstract**. This paper presents an analysis of a Switched Reluctance Motor (SRM) with modified special stator structure. The presented motor is designed to propel vehicles, in particular electric bikes. The paper determines the variability of the electromagnetic torque, self-inductance and mutual inductance. A control system for the SRM and simulation results of calculations concerning time plots for currents and electromagnetic torque of the examined converter are presented.*

***Streszczenie.** W artykule przedstawiono analizę stanów ustalonych przełączalnego silnika reluktancyjnego (SRM -Switched Reluctance Motor) o zmodyfikowanej geometrii stojana. Prezentowany silnik przeznaczony jest do napędu pojazdów elektrycznych, a w szczególności do roweru elektrycznego. W pracy wyznaczono zmienność momentu elektromagnetycznego, indukcyjności własnej oraz wzajemnej. Zaproponowano i przedstawiono układ sterowania dla silnika SRM, pokazano wstępne wyniki obliczeń przebiegów czasowych prądów oraz momentu elektromagnetycznego badanego przetwornika. (**Analiza stanów ustalonych silnika SRM o zmodyfikowanej geometrii stojana**)*

Keywords: e-bike, electric motor, electric vehicle, SRM, finite element method.
Słowa kluczowe: rower elektryczny**,** napęd elektryczny**,** przełączalny silnik reluktancyjny, metoda elementów skończonych.

Introduction

Electric vehicles are becoming a practical and convenient means of transport in busy urban agglomerations of the contemporary world. As the electric vehicles do not emit harmful exhaust fumes, their use does not contribute to air pollution or the global warming while additionally reducing acoustic noise [1,2,3]. The electric energy which powers the vehicle may come from renewable energy sources or use the kinetic energy recovered in the process of braking.

However, one disadvantage of electric vehicles is their short range between charges [5]. A solution to this problem may lie, among others, in the participation of countries in the creation of a modern infrastructure of electric vehicle charging stations. According to the Alternative Fuels Observatory, there currently are approximately 150 electric vehicle charging stations in Poland [6].

Nowadays, a wide variety of electric bikes are available, ranging from those equipped with a small motor which is designed to merely assist the cyclist to those featuring a more potent power unit, forming an electric unit in the style of a moped [4].

Three different concepts for the installation of electric motors to propel bikes are currently available on the market. The first variant is to integrate the motor with the chainset and the pedals. In this solution, power from the crankshaft is transmitted directly to the chain drive, and the central position of the motor makes it possible to maintain the correct centre of gravity in the bike. The second available and most common variant in serial production of electric bikes is a motor mounted in the front wheel hub. The third method for installing a motor in an electric bike is the rear wheel hub. This solution is similar to the one presented before; however, here the bike is more stable and may be used for off-road rides. In addition, the installation of the motor in the rear wheel provides better transmission of torque and enables the use of a freehub with a cassette for changing gear ratios [8,9,10].

An e-bike can reach a speed which does not exceed 25 to 32 km/h, depending on the regulations applicable in a given country. A speed limit of 25 km/h and a motor power limit of 250 W apply in Europe [11]. Given these limits, the maximum speed of an electric motor which powers a bicycle with 28-inch wheels will not be greater than 200 rev/min, with a transmission ratio of 1:1.

It is necessary to match the power unit to the structure depending on the size of the bicycle. In e-bikes, including other electric vehicles such as electric or hybrid cars, the trend is to use a motor with the highest torque density [12]. At the moment, the most common models are permanent magnet motors, which are characterised by good operating parameters but require considerable financial expenses due to the high price of rare-earth element (REE) [12,13,14]. Other machines used for vehicle propulsion are induction motors, conventional synchronous motors as well as SRM.

Switched reluctance motors are characteristics is similar to a DC motor, they have a simple structure and high torque density for wide speed range [15,16]. These types of motors may be used in structures in which the mounting location is not a critical condition. In case of electric vehicles, the most frequent location of the SRM motor is directly in driving wheels [1,13].

This paper proposes the use of a modified design of the SRM motor to support the gear ratio system in a bicycle. The proposed modification to the SRM motor stator makes it possible to reduce the weight and volume of the entire motor structure and, as a result, the operating conditions of a bicycle are improved and new possibilities of mounting the motor can emerge.

Modified Switched Reluctance Motor Structure

In this paper, the structure of the switched reluctance motor is illustrated in Figure 1. Thanks to the characteristic geometry of the stator (reduced machine diameter), it is possible to place the motor in the bottom bracket.

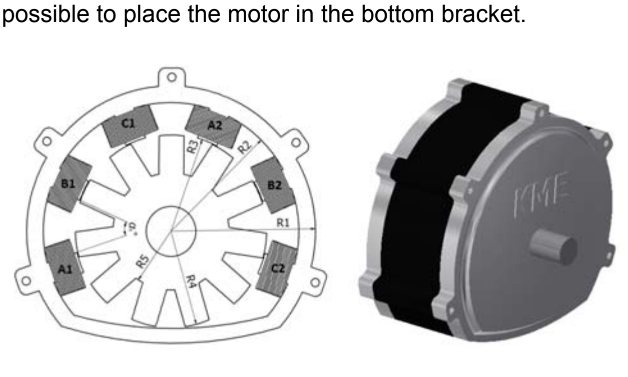

Fig. 1. A new SRM design

Due to the modification to the stator geometry, the bottom part of which constitutes a lock that closes the magnetic circuit between two border poles, it is possible to increase the radius of the rotor and, thus, to increase the value of the torque. This modification makes it possible to use the motor in vehicles with limited mounting space and install it in the lowest construction point of light vehicles, bicycles in particular. Table I shows selected SRM parameters.

Table 1. Selected parameters of new switched reluctance motor

SRM specification	***Value***	***Unit***
R1	87	mm
R2	77	mm
R3	58	mm
R4	57.6	mm
R5	35	mm
α_s	43.63	degrees
Number of stator poles	6	-
Number of rotor poles	11	-
Number of turns per pole	40	-
Stack length (*L*)	50	mm

Static Analysis of the SRM

The finite element method [17] is used to calculate the integral parameters of the examined motor. Given the unfavourable ratio of the active length to the converter diameter, a three-dimensional numerical model is developed. The calculations are performed in several stages, the first stage serves to determine the static characteristics. The constructed model considers the non-linear characteristics of magnetisation and assumes a constant current density across the inductors [18]. The characteristics of the electromagnetic torque (T_e), depending on the rotor position angle (α), are determined based on calculations for the current values assigned within a given band. The electromagnetic torque (T_e) for the 2D model is determined using the virtual work method.

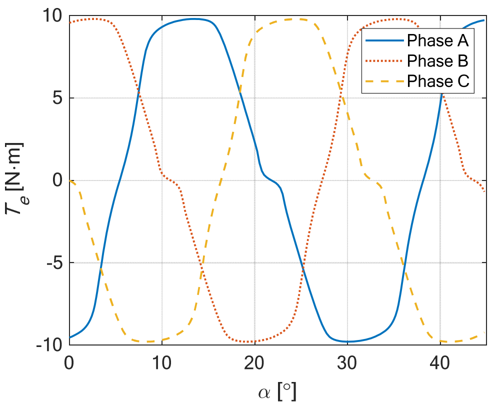

Fig. 2. Generated electromagnetic torque vs. rotor angle for each phase at a constant current value of *I*=35A

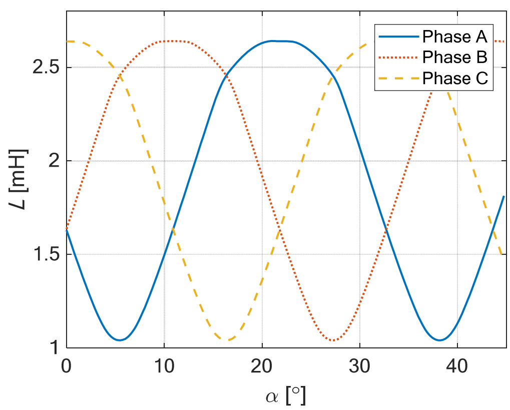

Fig. 3. Dependence of self-inductance of each phase vs. the rotor angle at a constant current value of *I*=35 A

Then the ratio of the incremental self-inductance of the phase to the rotor position angle (α) is determined (Fig. 3). The mutual-inductance of the phases is negligible because it is lower by 3 orders of magnitude.

Steady State analysis of the SRM

The next stage of the study includes the analysis of steady states during normal operation of the machine. The switched reluctance motor requires an electronic switching system. The model used a half-H bridge, which is the basic and the most frequently used control system in such solutions [19]. This study only uses two operating states of the half-H bridge. The first state is illustrated in Figure 4a. When transistors T_1 and T_2 are activated, the stator phase is powered. During this time, the rotor has to rotate in such a way as to achieve the position with the lowest magnetic reluctance for a given phase. The other state illustrated in Figure 4b makes it possible to return part of the energy stored in the drive to the power source.

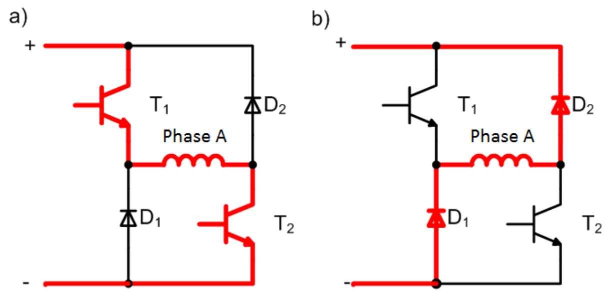

Fig. 4. Operating states of the half-H bridge

Based on the field-circuit model developed, the authors made calculations in order to determine instantaneous current waveforms and the torque in a steady state. To control the SRM motor, it is important to choose the appropriate control by activating individual phases. At first, a sequential activation of individual phases was used according to the algorithm presented in Fig. 5 (Cont. 1). Given a constant phase powering range, individual activation angles are selected in such a way as to achieve the maximum average electromagnetic torque. Figures 6 and 7 demonstrate examples of current waveforms in individual motor phases and the electromagnetic torque generated when voltage of *U*=24 V is applied.

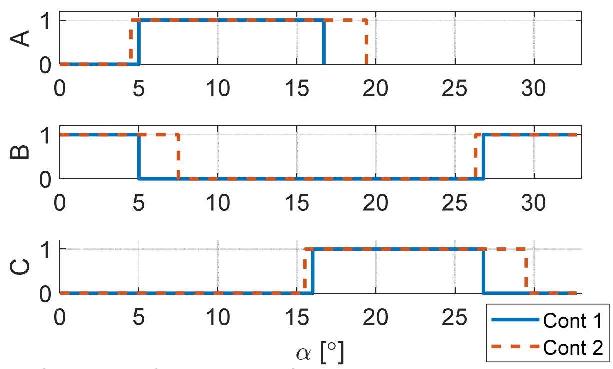

Fig. 5. Sequence of switching an SRM phase

Another stage involved the implementation of the Cont. 2 control algorithm (Fig. 5), in which both the activation and deactivation angles (Fig. 8 to 9) are changed. As a result, the electromagnetic torque ripple decreased considerably (Table 2), while the average value of electromagnetic torque increased.

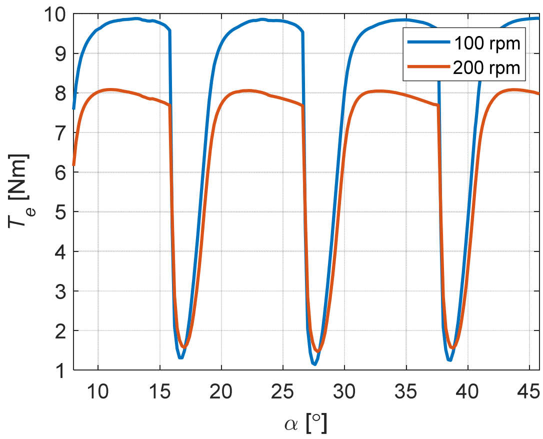

Fig. 6. Electromagnetic torque generated by the SRM when control is Cont. *1*

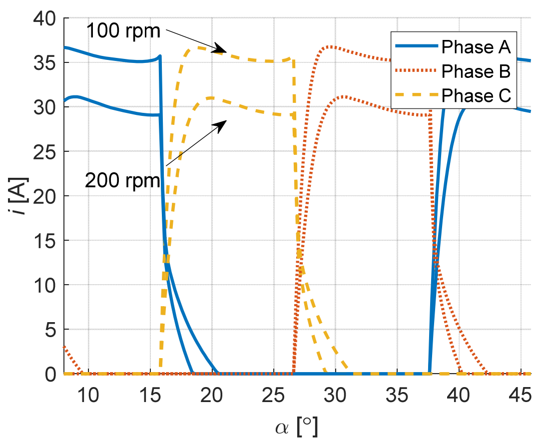

Fig. 7. Current waveforms in the SRM for Cont. 1

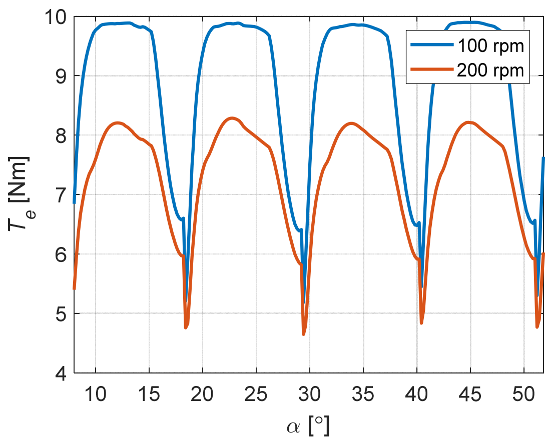

Fig. 8. Electromagnetic torque generated by the SRM when control is Cont. 2

In addition, the calculations provided the ripple (1) [20]:

$$\varepsilon = \frac{T_{max} - T_{min}}{2T_{av}} \cdot 100\% \quad (1)$$

where: T_{max} – max torque value, T_{min} – min torque value, T_{av} – average torque value.

Table 2. Selected parameters for 200 RPM

	T_{max} [N·m]	T_{av} [N·m]	ε [%]
Cont. 1	8.1	6.6	50
Cont. 2	8.3	7.3	25

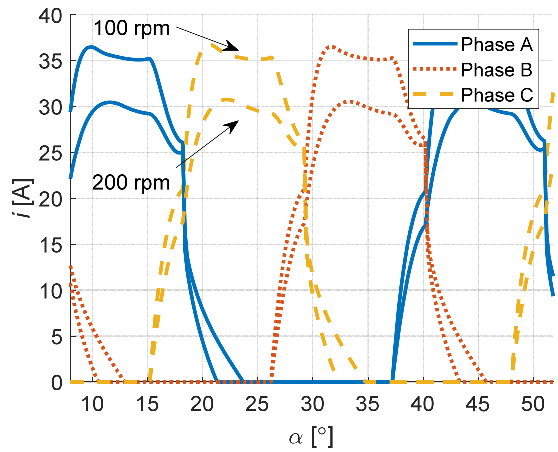

Fig. 9. Current waveforms in the SRM for Cont. 2

Summary

This paper presents a simulation study of the new SRM, designed to propel a bike. The integral parameters of the motor have been determined and a simulation analysis of the steady states has been presented.

Further studies will be carried out to optimise the engine design with a view to obtaining a higher average value of electromagnetic torque generated by the motor and reducing its ripple. Also, further studies will include a physical prototype of the modified SRM, which is under construction now.

***Authors**: dr inż. Piotr Mynarek, mgr inż. Rafał Gabor, dr inż. Marcin Kowol, dr inż.. Janusz Kołodziej, prof. dr hab. inż. Marian Łukaniszyn, Opole University of Technology, Faculty of Electrical Engineering Automatic Control and Computer Science, e-mail: p.mynarek@po.opole.pl, rafal.gabor@doktorant.po.edu.pl, m.kowol@po.opole.pl, ja.kolodziej@po.opole.pl, m.lukaniszyn@po.opole.pl*

REFERENCES

[1] Murakami S., Goto H., Ichinokura O., A Study about Optimum Stator Pole Design of Axial-Gap Switched Reluctance Motor, *International Conference on Electrical Machines (ICEM) Berlin*, Germany, pp. 975-980, 2014.

[2] Peng F., Lin J., Ye J., Emadi A., Optimal Calculation Method for Control of Switched Reluctance Motor. *McMaster Institute for Automotive Research and Technology*, McMaster, University Hamilton, Ontario, Canada, 2015.

[3] Inte R. A., Jurca F. N., A Novel Synchronous Reluctance Motor with Outer Rotor for an Electric Bike, *International Conference and Exposition on Electrical and Power Engineering*, Iasi, Romania, pp. 213-218, 2016.

[4] Chlebosz W., Ombach G., Junak J., Comparison of permanent magnet brushless motor with outer and inner rotor used in e-bike, *XIX International Conference on Electrical Machines*, Rome, Italy, 2010.

[5] Sun M., Chen H., Yan W., Cheng H., Liu Z., Design and Optimization of Switched Reluctance Motor for Propulsion System of Small Electric Vehicle, *IEEE Vehicle Power and Propulsion Conference*, 2016.

[6] http://www.orpa.pl (access 2018)

[7] https://www.statista.com/statistics/397765/electric-bicycle-sales-in-the-european-union-eu (access 2018)

[8] Evtimov I., Ivanov R., Staneva G., Kadikyanov G., A Study on electric bicycle energy efficiency, *Transport Problems*, Volume 10, Issue 3, pp. 131-140, 2015.

[9] Chlebosz W., Ombach G., Junak J., *Analysis and optimization of drive system used in electric bike*, Journal of Electrical Engineering, 2010.

[10] Muetze A., Tan Y. C., Electric bicycles, *IEEE Industry Magazine*, pp. 12-21, July/August 2007.

[11] Thomas D., Vallée F., Klonari V., Ioakimidis C.S., Implementation of an E-bike Sharing System: The Effect on Low Voltage Network using PV and Smart Charging Stations, *4th International Conference on Renewable Energy Research and Application*, pp.573-577, 2015.

[12] Argiolas O., Nazeraj E., Hegazy O., De Backer J., Mohammadi A., Mierlo J., Design Optimization of a 12/8 Switched Reluctance Motor for Electric and Hybrid Vehicles, *Twelfth International Conference on Ecological Vehicles and Renewable Energies*, 2017.

[13] Anvari B., Toliyat H. A., Fahimi B., Simultaneous Optimization of Geometry and Firing Angles for In-Wheel Switched Reluctance Motor, *IEEE Transactions on Transportation Electrification*, pp.322-329, 2018

[14] Peng F., Lin J., Ye J., Emadi A., Optimal Calculation Method for Control of Switched Reluctance Motor, *IEEE Transportation Electrification Conference and Expo*, 2015.

[15] Miller T.J.E., Optimal Design of Switched Reluctance Motors, *IEEE Transactions on Industrial Electronics*, Volume 49, Number 1, pp. 15-27, February 2002.

[16] Çinar M.A., F. E. Kuyumcu, Design and Drives Simulation of an In-Wheel Switched Reluctance Motor for Electric Vehicle Applications, *IEEE International Electric Machines & Drives Conference*, pp. 50-54, 2007.

[17] Flux3d, User's guide, vol. 1-4, 2013.

[18] Gabor R., Kowol M., Kołodziej J. , Mynarek P., Steady State Analysis of Switched Reluctance Motor with Modified Geometry of the Stator Designed for an Electric Bike, *International Symposium on Electrical Machines*, Kocierz, Poland, 2018.

[19] Tomczewski K., Wróbel K., Improved C-dump converter for switched reluctance motor drives, *IET Power Electron*, Vol. 7, Iss. 10, pp. 2628- 2635, 2014.

[20] Tomczewski K., Wach P., Wróbel K., Model and Experimental Investigations of SR Oscillatory Motor, *Przegląd Elektrotechniczny*, 10'2005.