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ANALYSIS OF ENERGY-SAVING STRUCTURES OF ELECTRIC MACHINES FOR DOMESTIC DRIVE

ANALIZA ENERGOOSZCZĘDNYCH KONSTRUKCJI MASZYN ELEKTRYCZNYCH NAPĘDÓW SPRZĘTU AGD

Abstract

In the paper, alternative technologies of electric machines for domestic appliances were discussed. Nowadays, domestic appliances are used on a mass scale. In most households, there are domestic appliances where electric machines are used. Commutator motors are generally used in domestic appliances due to low costs of production. This is one of their few advantages, whereas to their disadvantages can include low energy efficiency and durability, which is limited by the sliding contact of brush-commutator. In consequence, devices equipped with these motors have low efficiency of energy conversion and are very often unreliable. In recent years, the vacuum cleaner became the receiver of relatively high power from the mains. Therefore, vacuum cleaners were covered by EU regulations. An increase of the energy efficiency of domestic appliances where electric machines are used is possible, among others, by introducing energy-saving technologies in electric machines. They are characterized not only by higher energy efficiency, but also by much longer failure-free operation of domestic appliance drive.

Keywords: domestic drive, commutator motor, brushless motor direct current motor; BLDCM; SRM; mechanical characteristics, waveforms

Streszczenie

W artykule omówiono alternatywne technologie maszyn elektrycznych możliwe do zastosowania w sprzęcie AGD. W większości gospodarstw znajduje się sprzęt AGD, w których są stosowane maszyny elektryczne. Zazwyczaj w sprzęcie AGD stosuje się silniki komutatorowe. Są one stosowane ze względu na niskie koszty produkcji. Jest to ich jedna z nielicznych zalet. Natomiast ich wadą jest niska sprawność energetyczna oraz trwałość ograniczona istnieniem zestyku ślizgowego szczotka-komutator. W konsekwencji urządzenia wyposażone w te silniki charakteryzują się niską sprawnością przetwarzania energii oraz znaczną awaryjnością. Jednym z urządzeń sprzętu AGD który w ostatnich latach stał się odbiornikiem o stosunkowo dużej mocy pobieranej z sieci zasilającej jest odkurzacz. Z tego też powodu stał się on obiektem wprowadzonych obecnie obostrzeń w Unii Europejskiej. Wzrost efektywności energetycznej sprzętu AGD, wykorzystującej maszyny elektryczne możliwy jest m.in. poprzez stosowanie energooszczędnych technologii maszyn elektrycznych. Charakteryzują się one nie tylko wyższą efektywnością energetyczną, ale również zapewniają znacznie dłuższą pracę bezawaryjną układu napędowego sprzętu AGD. W artykule porównano właściwości klasycznego silnika z komutatorem mechanicznym z właściwościami maszyn z komutacją elektroniczną typu BLDC i SRM. Zamieszczono wyniki badań laboratoryjnych autorskiego prototypu silnika reluktancyjnego przełączalnego do napędu agregatu ssącego odkurzacza.

Słowa kluczowe: napęd sprzetu AGD, silniki bezszczotkowe prądu stałego, BLDCM, SRM, charakterstyki mechaniczne, przebiegi czasowe

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1. Introduction

Domestic appliances, which are used on a mass scale in households, contribute to energy consumption on the European or the global scale. The energy efficiency improvement of electric devices used in domestic appliances has recently been a priority of the EU. An example of such domestic appliance can be a vacuum cleaner, which is used in almost all households. It is estimated that, in Poland alone, there are over 13 million of such devices. Vacuum cleaners were covered by EU regulations, which introduced limitations of input power consumed by them in order to decrease the global energy consumption [1]. Electric motors used in vacuum cleaners consume power, which has significant influence on the overall power consumption. In almost all vacuum cleaners, a classic electric motor with a mechanical commutator, which has many disadvantages like low efficiency or low durability of sliding contact of brush-commutator, is generally used. One of the directions of the development of electric drives used in vacuum cleaners, which can cause a limitation of the global energy consumption, is the application of energy-saving electric machines with electronic commutation.

The aim of the paper is to show test results of the novel drive with an electric motor with electronic commutation and to assess its energy efficiency in comparison with the classic motor with a mechanical commutator [2].

In the paper, a comparison of the properties of a classic electric motor with a mechanical commutator and a motor with an electronic commutation was presented. Results of laboratory tests of the novel switched reluctance motor prototype for a suction unit drive of a vacuum cleaner were presented. Finally, conclusions concerning the benefits of using energy-saving machines in vacuum cleaner drives were presented.

2. Energy-saving structures of electric machines

Brushless electric motors with electronic commutation belong to alternative technologies of electric machines [2–6]. The following structures can be included: brushless motors with permanent magnets (BLPM) and switched reluctance motors (SRM). Brushless machines with permanent magnets can be divided into: brushless DC machines with permanent magnets (BLDC) and synchronous machines with permanent magnets (PMSM). Brushless DC motors with permanent magnets, where the classic commutator is replaced by a dedicated power electronics system with a control system, are preferred in domestic appliances. Both structures of motors differ significantly from each other despite the common thing, which is the electronic commutator. Fig. 1 shows the structures of a classic commutator motor (Fig. 1a), a brushless DC motor with permanent magnets (Fig. 1b) and a switched reluctance motor (Fig. 1c).

The classic structure of a commutator motor has a wound rotor. The electromagnetic torque is produced by the interaction of a magnetic field between stator winding and rotor winding. The mechanical commutator allows to change the direction of current in individual coils of rotor winding. The mechanical commutator is the weakest element of this kind of motors. In a brushless DC motor, the electromagnetic torque is produced between a magnetic field generated by stator winding and a magnetic field from permanent magnets mounted on the rotor. In a switched reluctance motor, a magnetic field is produced only by stator winding. The electromagnetic torque is produced due to the minimization of the reluctance between the stator and the magnetic field of the rotor. Therefore, the rotor tends to the position where reluctance is the smallest. In both BLDC and SRM motors, commutation of currents in stator phases must occur during the rotation. In Table 1, the most important properties of structures shown in Fig. 1 are presented.

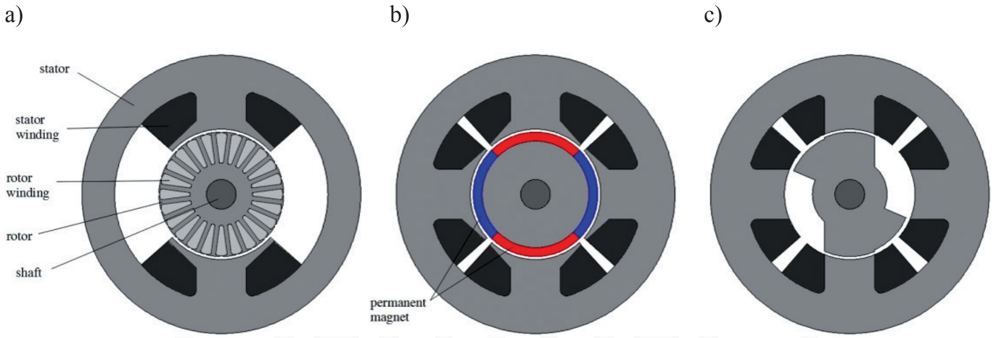

Fig. 1. Structures of: a) the classic commutator motor, b) the brushless DC motor, c) the switched reluctance motor

The authors were designing high-speed classic (commutator) motors and brushless motors with electronic commutation (both BLDC and SRM) for the suction unit drive, which should fulfil current restrictions associated the with power consumption from the mains. During the design process, it was assumed that the motors should provide power on the shaft of no less than 700 W at a speed of 45000 rpm. The classic commutator motor should provide the required power at a lower speed. Such a high speed is caused by using a single-stage turbine, which produces subatmospheric pressure. Additionally, it was assumed that their structure should provide the possibility to mount standard bearing discs and a suction unit from one of domestic appliances manufacturers. In Table 2, chosen results of simulation tests of both designed structures at rated working point are presented.

Table 1

Chosen properties of structures from Fig. 1

	Commutator motor	**BLDCM**	**SRM**
Direct AC supply	yes	No	No
Number of phases	1	1	recommended 2
Start-up torque	high	medium	medium
Power electronics system	recommended	required	required

cd. Tab. 1

Smooth start-up	possible	yes	yes
Range of speed regulation	wide	wide	wide
Possibility of input power control	very hard	possible	possible
Efficiency	average	high or very high	high
Protection of motor for high-speed operation	required	required	not required
Necessity of using rotor position sensors	unnecessary	recommended	required
Influence of temperature on the rotor	Serious – problems with heat dissipation from rotor	Serious – change of permanent magnets parameters with temperature	No effect
Typical motor durability	Average – limited mostly by durability of sliding contact of brush-commutator	High – limited mainly by durability of bearings	High – limited mainly by durability of bearings

Table 2

Chosen tests results of designed structures of motors for suction unit

Parameter/Type of motor	**commutator**	**BLDCM**	**SRM**
Supply voltage U [V]	230 AC	320 DC	320 DC
Input power P_{in} [W]	1202	896	896
Output power P_{out} [W]	708	706	700
Speed at rated power n [rpm]	35000	45000	45000
Motor efficiency h_M [%]	59.5	80.4	79.8
Overall efficiency h [%]	–	78.8	78.1
Electromagnetic torque ripple e [%]	365	112	352
Length of stator stack L_{Fe} [mm]	25	15	20

Both of the designed structures do not consume more than 900 W from the mains at the required working point, but at the same time, they produce the required output power on the shaft. The overall efficiency of the BLDC motor is slightly higher (78.8%). In a switched reluctance motor, the efficiency obtained in simulation tests was slightly lower and equaled

78%. The commutator motor definitely has the lowest efficiency (59.5%). However, after using the speed control, the system efficiency will be more reduced. All motors are characterized by rather high ripples of the generated electromagnetic torque. It is caused by high maximum values of generated electromagneic torque T_{emax} and small minimum values of electromagnetic torque T_{emin}. Electromagnetic torque ripples were calculated from equation:

$$\varepsilon = \frac{T_{e\max} - T_{e\min}}{T_{eav}} \tag{1}$$

where:

$T_{e\max}$ – maximum electromagnetic torque,
$T_{e\min}$ – minimum electromgnetic torque,
T_{eav} – average electromagnetic torque.

The BLDC motor has the smallest torque ripple (112%). A higher number of phases can significantly decrease them, but this is associated with significantly higher costs of production of the power electronics system. The same situation is present in a switched reluctance motor. In a two-phase switched reluctance motor, it is possible to significantly limit ripples of the generated electromagnetic torque by using e.g. current regulation [6]. A power electronics system, which allows a much faster energy return, is another possibility of ripples limitation [7]. In a commutator motor supplied directly from AC network, there is no possibility to limit ripples of the electromagnetic torque. Ripples are directly connected with the shape of the motor current. However, compared to brushless motors with electronic commutation, in a commutator motor, the basic frequency of ripples of the generated electromagnetic torque equals the power frequency and it does not depend on the motor speed. The length of the commutator motor stack is definitely the longest. The BLDC motor has the shortest stack length.

3. Results of laboratory tests of the prototype SRM motor

The switched reluctance motor was made and tested in laboratory conditions. Fig. 2 shows the classic commutator motor and the prototype of switched reluctance motor, both with comparable electric parameters.

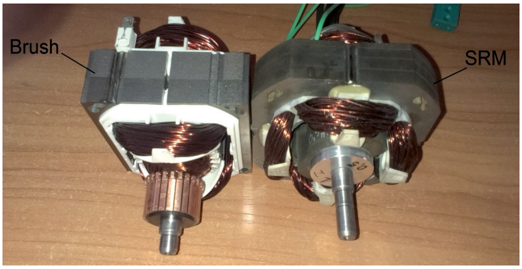

Fig. 2. An example of the commutator motor and the prototype of switched reluctance motor

Tests in laboratory conditions were conducted for the prototype of switched reluctance motor. The influence of the control parameters on features of the prototype was tested. Due to limitation of the maximum speed of the eddy-current dynamometer ($n_{\max}$ = 50000 rpm), all tests corresponding with simulation conditions were not conducted. Figs. 3–4 show exemplary dependence of speed n on the function of load torque T_L for various control parameters i.e.

– variable conduction angle θ_c = var and constant turn-on angle θ_{on} = const,
– variable turn-on angle θ_{on} = var and constant conduction angle θ_c = const

at decreased value of supply voltage (U_{dc} = 100 V).

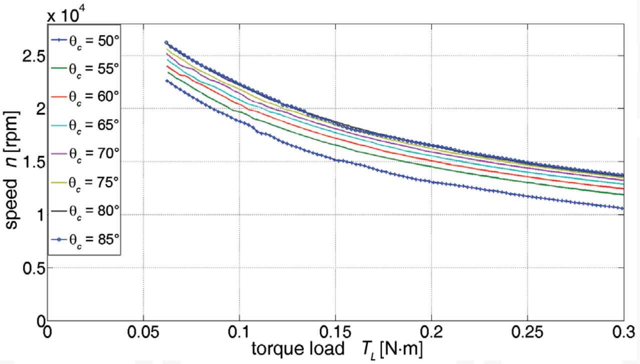

Fig. 3. Mechanical characteristics of the switched reluctance motor prototype obtained in laboratory conditions at variable conduction angle and constant turn-on angle

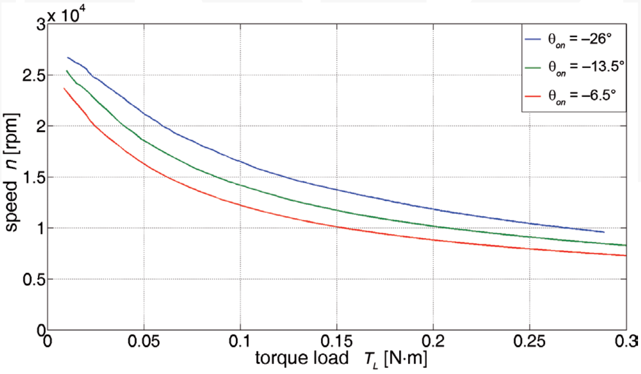

Fig. 4. Mechanical characteristics of the switched reluctance motor prototype obtained in laboratory conditions at variable turn-on angle and constant conduction angle

By changing the control parameters, it is possible to regulate speed in a very wide range. Therefore, it is possible to obtain the required working point by changing the control parameters of a motor even at decreased supply voltage ($0.9U_N$). The statement of laboratory test results was prepared to compare the switched reluctance motor prototype with the commutator motor. Tests of the switched reluctance motor were conducted at control parameters, which do not allow reaching a speed of 50000 rpm. The commutator motor was tested at supply voltage equaling $U = 230$ V AC. Figs. 5–6 show the dependence of speed n (Fig. 5) and efficiency (Fig. 6) on the function of the load torque T_L.

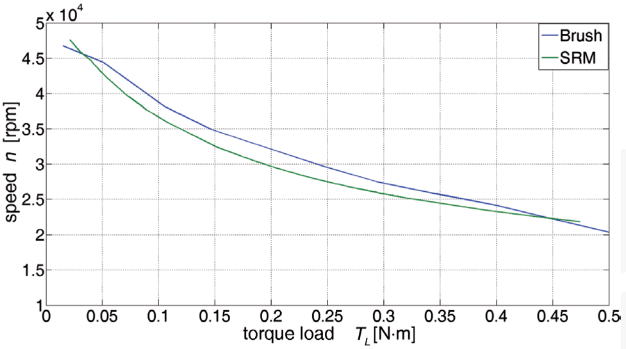

Fig. 5. Mechanical characteristics of the commutator motor and the switched reluctance motor from laboratory tests

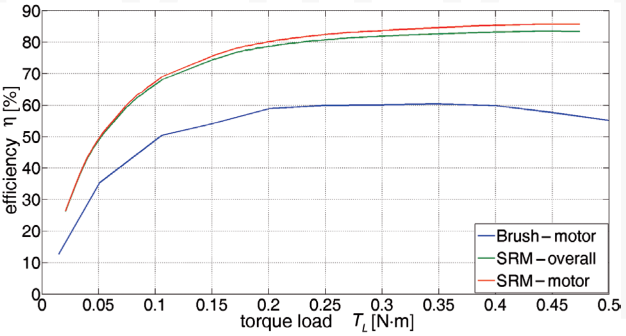

Fig. 6. Efficiency characteristics of the commutator motor and the switched reluctance motor from laboratory tests

The obtained mechanical characteristic of the switched reluctance motor prototype is below the characteristic of the commutator motor due to forced control parameters, which limit the maximum speed of the motor. Despite the limited speed, the overall efficiency of the switched reluctance motor equals 83.4%, whereas the efficiency of the alone motor equals 85.7%. In the case of the commutator motor, efficiency equals 60.4%. The commutator motor was tested without a control system of the motor speed, but even after using such a system, the efficiency of the motor will be slightly decreased. This is caused by the changing current shape (Fig. 7), which is caused by the operation of the speed control system.

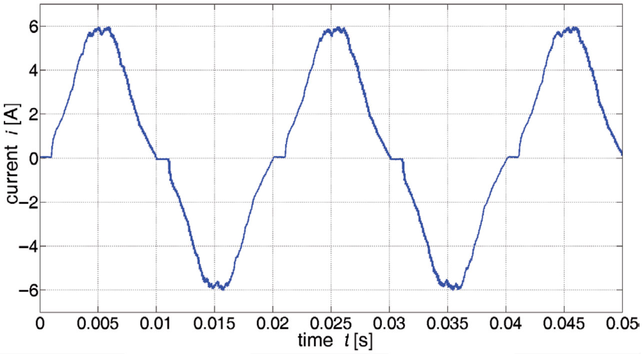

Fig. 7. Waveform of current of the commutator motor after mounting the speed control system

The tested prototype of the switched reluctance motor achieved much higher efficiency (about 23%) than the commutator motor, despite the limited output power. The efficiency of the prototype alone was higher by about 25.3%. The stator stack of the prototype switched reluctance motor was 25% shorter than the stack of the commutator motor at the same outer diameter of the rotor. Nevertheless, a 20% increase in the output power was achieved at the same value of input power. It is a very desirable with respect to current energy efficiency classes and classes, which will be applied after 01.09.2017. It should also be noted that, when the commutator motor will consume less than 900 W from the mains, the efficiency will be significantly lower. In the case of the brushless DC motor with electronic commutation, the overall efficiency will also be decreased when output power will be lower. However, the difference between the classic commutator motor and the brushless DC motor with electronic commutator will decrease, but for the benefit of the second one.

4. Conclusions

The application of energy-saving electric machines with electronic commutation in suction unit drives of vacuum cleaners on a mass-scale is one of the directions of the development of vacuum cleaners. However, on the one hand, it can cause a decrease in the global energy consumption, but on the other hand, customers will pay all of the costs, which are associated with the introduction of domestic appliances with improved energy efficiency. The purchase of a vacuum cleaner with an energy-saving motor should guarantee at least over a decade of failure-free operation. The domestic appliance with the A class or higher could be profitable only when the lifetime of this device will be significantly extended. The extension of failure-free operation of most domestic appliances with electric motors to about 10 years by using energy-saving electric machines can cause both a limitation of the global energy consumption by individual consumers, but also a limitation of e-waste production. This way, using much more expensive technologies could have a greater influence on the increase of consumers' awareness. Unfortunately, during the current tendency of domestic appliance manufactures to reduce the lifetime of their products, the purchase of an energy efficient device is not economically justified. Therefore, this is a very serious problem, which has to be solved not only on the country scale, the European scale, but also on the global scale. One of the ways of solving this problem is to force manufacturers of domestic appliances with energy-saving technologies to extend the failure-free operation time. The paradox of history is that domestic appliances which, were produced decades ago, allowed for operation over decades, despite the lack of formal guarantees of such long failure-free operation. However, the parameters of such devices were far from desirable. The application of modern energy-saving technologies allows for the increase of operation efficiency of the domestic appliance with a significant increase of its energy class. This should be the main aim of introducing new energy efficiency norms of chosen domestic appliances.

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