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Output Power of Switched Reluctance Generator with regard to the Phase Number and Number of Stator and Rotor Poles

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Introduction

A switched reluctance generator (SRG) belongs to the new, modern types of brushless, electronically commutated, rotating electrical machines. The switched reluctance machines have been investigated in motoring mode by many researchers during the latest few decades [1], [2]. As all electrical machines also SR-machines work reciprocal but the generating mode has been rarely studied. The generating mode of this machine is interesting for many applications and therefore it is important to investigate its performances [3].

An advantage of the generator is, that it can operate also as a single or two phase machine, because it does not need to start up by means of rotating magnetic field like the motor. The authors dealing with these topics, recommend to use a high number of poles and phases for lower range of speeds and lower phase number for high speed range.

Some authors, e.g. [4], deal only with single phase SRG with 8/8 topology, or better to say, in the single phase configuration there is always considered that number of stator and rotor poles are equal $N_s = N_r$. Besides the single phase SRG, most frequent are three-phase configurations, with 6/4 [5], [6], 12/8 [7], or 24/16, or even the 16/12 poles. The high speed SRGs are recommended to employ in cars or aircraft industry, and even in the cars they can be used as starter/generator. In general, the SR machines are suitable for high temperature operation, because there are no PMs and no rotor windings, and therefore almost all losses are dissipated only in the stator. The phase and pole number influence the current ripple of the SRG and switching frequency. The saliency ratio, given by L_{max} / L_{min} , depends on the dimensions, shapes and length of the poles and air gap, what is important for the optimal electromechanical energy conversion.

In this paper an interest will be focused on the investigation of various phase numbers and number of stator and rotor poles. An optimal topology of SRG magnetic circuit from the point of view of achieved output power is investigated. On the base of SRG mathematical model the output power is simulated for two kinds of single phase and five kinds of multiphase topologies. Some measurements are carried out in motoring mode and compared with FEM investigations and simulations to verify mathematical model of SR machine. A real SR machine is investigated and optimized with the following ratings 12/8, 3.7 kW, 3000 rpm and 18 A, what is the measured rms value for rated motoring operation. The cross section area of a real SRG basic topology can be seen in Fig.1.

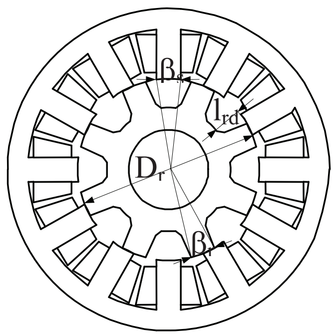

Fig. 1. The cross-section area of SRG called a basic topology

Methodology, equivalent circuit and simulation model of SRG

To be able to investigate performances of various kinds of SRG topologies, a reliable simulation model must be created and verified. Our approach was to create a simulation model for a real SR machine, which originally has been operated as a motor. Its cross section area is on Fig. 1. This topology will be called a "basic topology". A converter power circuit of one phase winding, including power part of the converter is on Fig.2. There are seven unknown variables for which seven equations are needed:

$$\frac{di_{ph}}{dt} = \frac{1}{L_{ph}}\left[v_{ph} - \left(R_{ph} + \frac{dL_{ph}}{d\theta}\omega\right)i_{ph}\right], \quad (1)$$

$$i_{in} = \begin{cases} i_{ph}, \text{ (S}_1 \text{ and S}_2 \text{ are switched ON)}, \\ 0, \text{ (at least one of S}_1\text{,S}_2 \text{ is switched OFF)}, \end{cases} \quad (2)$$

$$i_{out} = \begin{cases} i_{ph}, \text{ (S}_1 \text{ and S}_2 \text{ are switched OFF)}, \\ 0, \text{ (at least one of S}_1\text{,S}_2 \text{ is switched ON)}, \end{cases} \quad (3)$$

$$v_{ph} = \begin{cases} v_{DC}, \text{ (S}_1 \text{ and S}_2 \text{ are switched ON)}, \\ -v_{DC}, \text{ (S}_1 \text{ and S}_2 \text{ are switched OFF)}, \\ 0, \text{ (only one from S}_1\text{,S}_2 \text{ is switched ON, or } i_{ph}=0), \end{cases} \quad (4)$$

$$i_c = \sum_{j=1}^{m} i_{out_j} - \sum_{j=1}^{m} i_{in_j} - i_L, \quad (5)$$

$$i_L = \frac{v_{DC}}{R_L}, \quad (6)$$

$$\frac{dv_{DC}}{dt} = \frac{1}{C}i_c, \quad (7)$$

where the first four are for phase variables (phase current i_{ph}, input current i_{in}, output current i_{out} and phase voltage v_{ph}) and their values must be simulated for each phase winding extra. The last three equations are common for the whole generator: capacitor current i_c load current i_L and DC voltage.

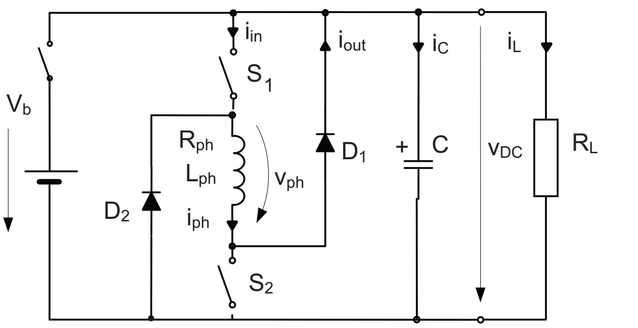

Fig. 2. A converter power circuit for SRG operation with two switchers per phase

There is a period of excitation and a period of generation. An exciting current, here called as an input current i_{in} equals to the phase current, if both switchers - transistors are switched on (2). A generated current here called as an output current i_{out} equals to the phase current during the period of diodes conducting (3).
The phase voltage can achieve $+v_{DC}$ during excitation or -v_{DC} during generating period (4). The total capacitor current is created as a difference between output currents and input currents of all the phases and load current. If the SRG starts to operate, obviously is excited from the external source, e.g. from battery with voltage V_b. For simulation there must be limitation

$$v_{DC} \geq V_b. \quad (8)$$

The output of the model is power on the load

$$p_{out\_L} = i_L v_{DC} \quad (9)$$

and output power

$$p_{out} = i_{out} v_{DC}. \quad (10)$$

If the power on the load and the output power are equal, SRG is in steady state condition. As it can be seen from (9) and (10), the output powers are calculated from electrical values of voltage and current. The input mechanical power is also possible to calculate, if all losses are known and they are added to output power. In this paper, during optimization process the power given by (10) is investigated. Simulation outputs made on the base of the presented simulation model have been verified by experiments and a coincidence was very good. It was described in greater details in [8].

SR machine experimental verification in motoring mode

To interpret an employment of the created mathematical model a real SR machine was investigated: 12/8, 3-phase, 3.7 kW, 3000 rpm. The stator and rotor are shown in Fig. 3. This real SRM (Fig.3) has been investigated by several test methods under static and dynamic conditions.

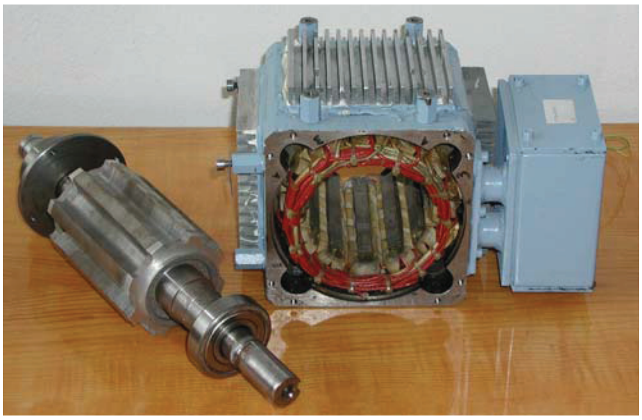

Fig. 3. The stator and rotor of investigated SRG

The static parameters (phase inductance, flux linkage, torque) have been investigated by means of FEM program, where nonlinear *B-H* curve was used. These parameters have been verified by measurements. These parameters are valid for both motoring and generating mode. It has been investigated in [9].

The dynamic performances have been simulated under Matlab program and compare with measurements. In Fig.4 there are shown phase voltage and current waveforms in motoring mode for low speed 500 rpm. As can be seen in these figures, also dynamic performances are in very good coincidence, and therefore the simulation model can be used for optimization of SRG magnetic circuit. For more details of SRM parameters investigation, see [9].

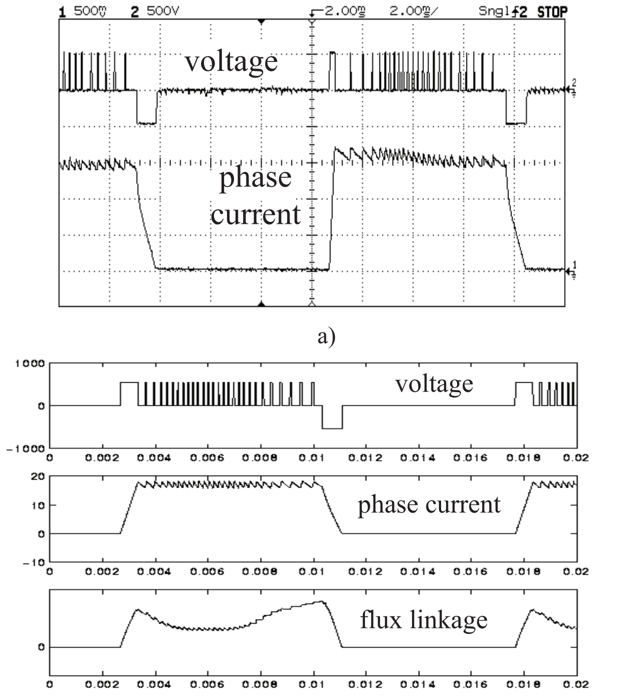

Fig. 4. Comparison of phase voltage and current waveforms for low speed of real SRM, a) simulation analysis, b) measurement

Optimization of SRG magnetic circuit

The magnetic circuit of the SRG mentioned in the introduction has been subjected to optimization procedure from the point of view of maximum energy conversion. The next parameters remain constant during all procedures:

1) Outer dimensions of the machine, such as outer stator diameter, effective length of iron, length of air-gap;
2) Speed 3000 rpm (SRG was in single-pulse operation);
3) DC voltage 540 V;
4) *B-H* curve of the iron material;
5) Apparent power of the converter;
6) Winding losses (210W). Because of heat removal it was important to keep also the total losses on the constant value to avoid overheating of the machine;
7) The converter losses have been neglected.

The basic topology is a three phase, 12/8 topology. The number of stator poles is always an even multiplying of the phase number

$$N_s = mi\,, \tag{11}$$

where i=2,4,6,…n and m is phase number. The number of rotor poles is always even, different from the number of stator poles and is divisible by the number of stator poles per phase

$$N_r = N_s \pm \frac{N_s}{m}\,. \tag{12}$$

The exception for generating operation is a single phase topology, in which is obviously $N_r = N_s$. Therefore here are investigated the next three phase topologies: 6/4, 6/8, 12/8, 12/16, see Fig. 5.

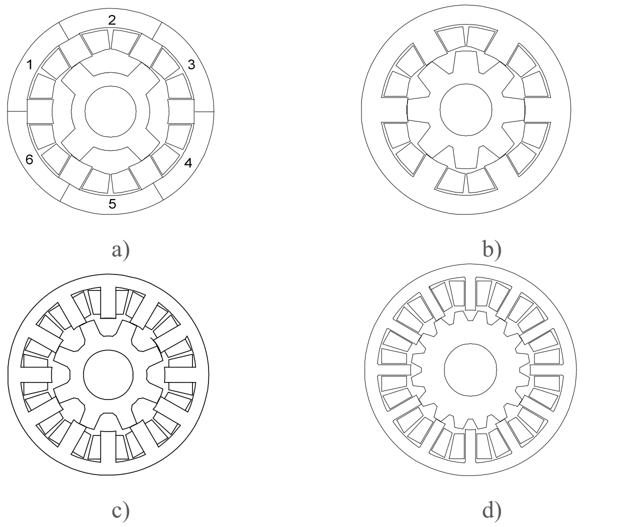

Fig. 5. Three phase SR machines with a) 6/4 topology and marked parts of the stator yoke, b) 6/8, c) 12/8, d) 12/16

In Table 1 there are parameters which correspond to the various number of stator and rotor poles for three phase topology. Number of strokes per one revolution of the rotor is

$$N_{wc} = mN_r \tag{13}$$

and fundamental frequency of the phase current is

$$f_{iph1} = \frac{n}{60} N_r\,. \tag{14}$$

The variables N_{wc} and f_{iph1} depend only on the number of rotor poles, and don't depend on the number of the stator poles. The frequency f_{iph1} is simultaneously fundamental frequency of the stator magnetic flux flowing through the stator poles or stator yoke. On the other side the fundamental frequency of the rotor flux f_{r1} depend on the number of the stator poles

$$f_{r1} = \frac{nN_s}{120m}\,. \tag{15}$$

Magnetic flux of the rotor pole makes one period if one rotor pole moves from one stator pole to the next one of the same phase with the same polarity of magnetic flux. It means that for SRG with two poles per phase, as for example three phase 6/4 type, is a period of rotor flux equal to period of one revolution, in the case of SRG with four poles per phase, e.g. three phase 12/8, it is a half of revolution, etc. Both frequencies influence iron losses in corresponding parts of magnetic circuit therefore it can be said: the higher number of poles, the higher frequency f_{iph1} or f_{r1}, what results in higher iron losses. For example, the idealized total rotor yoke flux linkage waveforms constructed from rotor yoke flux linkage waveforms created by phases A, B and C is shown in Fig.6.

Table 1. The parameters of various SRG topologies

Number of stator/rotor poles	N_s/N_r	6/4	6/8	12/8	12/16
Rotor pole pitch	α_{pr} (°)	90	45	45	22.5
Stator pole pitch	α_{ps} (°)	60	60	30	30
Stroke angle	ε (°)	30	15	15	7.5
Strokes per revolution	N_{wc}	12	24	24	48
Fundamental frequency of the stator phase current	f_{iph1} (Hz)	200	400	400	800
Fundamental frequency of the rotor flux	f_{r1} (Hz)	50	50	100	100

In the Table 1., the stator fundamental frequency seems to be much more higher than rotor one, what could recall a meaning that stator iron losses will be higher than the rotor one. It is not true, because it depends on the real waveform of the magnetic flux:

In the stator there is a triangular waveform, therefore a dominant influence has fundamental and the third harmonic components.

In the rotor there is a waveform much more disturbed therefore harmonics higher than third influence the losses, as it is seen in Fig. 6. There is seen, that eddy current losses in the stator parts are created by the 1^{st}, 2^{nd} and 3^{rd} harmonics, and in the rotor parts by the 5^{th}, 7^{th}, 9^{th} and 11^{th} harmonics, what is the same range of frequencies as in the stator.

In Fig. 8 there is shown, how the eddy currents contribute to the total losses in individual parts of the 6/4 SRG from Fig. 5a. The rotor losses create about 35% of the total losses but the rotor mass is only 31% of the total magnetic circuit mass.

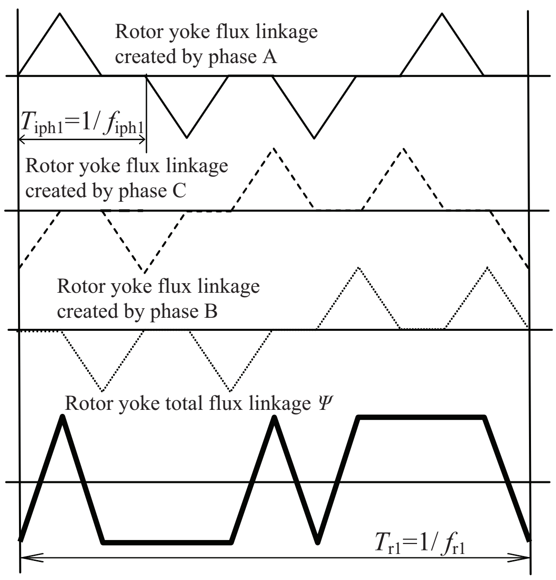

Fig. 6. The idealized rotor yoke flux linkage waveforms constructed from stator pole flux linkage waveforms of phase A, B and C

On the base of equivalent circuit shown in Fig. 2 and the consequent equations (1) – (7), the output power of the three-phase SRG with 6/4, 6/8, 12/8 and 12/16 topologies has been simulated.

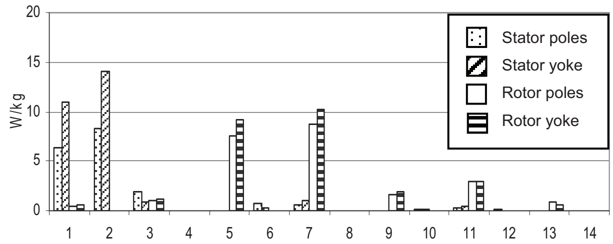

Fig. 7. Eddy current losses per kg in particular parts of SRG versus harmonics

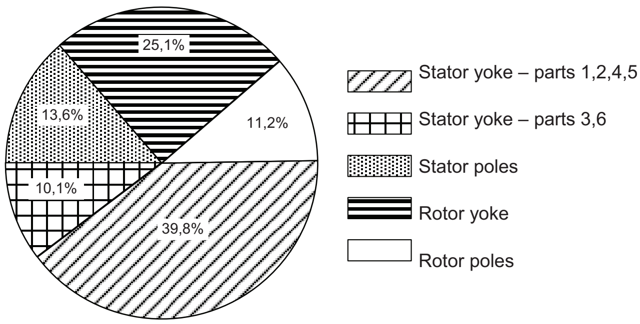

Fig. 8. Comparison of eddy current contribution in particular parts of 6/4 SRG

To achieve an objectivity at their comparison, also the next conditions have been kept:

1) The constant rotor diameter;
2) The thickness of the stator yoke and stator pole is equal with regard to the fact that stator yoke eddy currents create the biggest part in the total loss amount (see Fig. 8);
3) The lengths of the stator and rotor poles ensure that in unaligned position the poles are not partly overlapped. If yes, the L_{min} in unaligned position would increase and the saliency ratio L_{max} / L_{min} would decrease what results in a reduction of the power. Under these conditions the values of simulated output power are not very different, as it is seen in Fig 9.

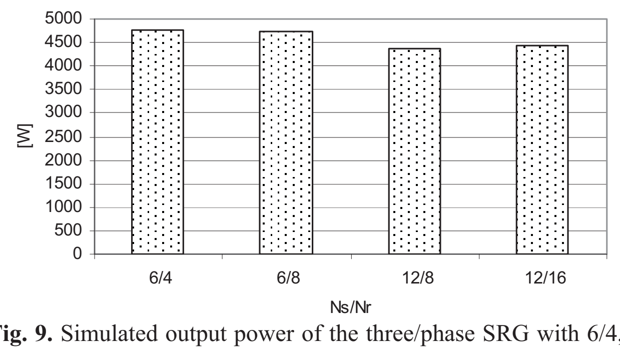

Fig. 9. Simulated output power of the three/phase SRG with 6/4, 6/8, 12/8 and 12/16 topologies

Changing of the phase number

Besides the three phase topology, the output power of the SRG was simulated also for single phase, two and four phase topologies, see Fig. 10. Their parameters depending on the number of poles and phases are shown in the Table 2.

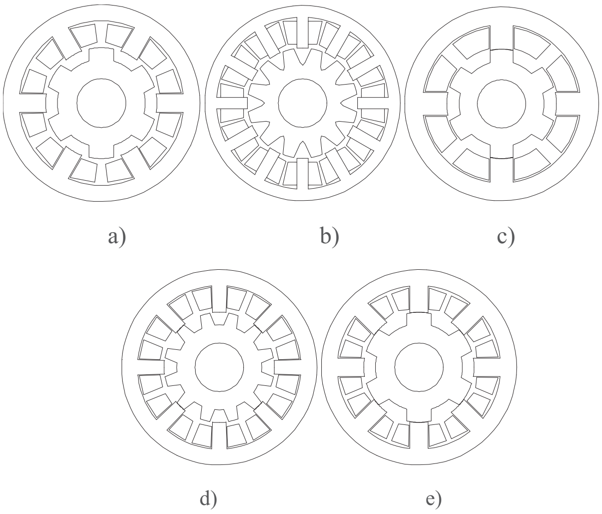

Fig. 10. Cross-section areas of SRG topologies with various phase numbers, a) single phase 6/6, b) single phase 12/12, c) two phase 4/6, d) two phase 8/12, e) four phase 8/6

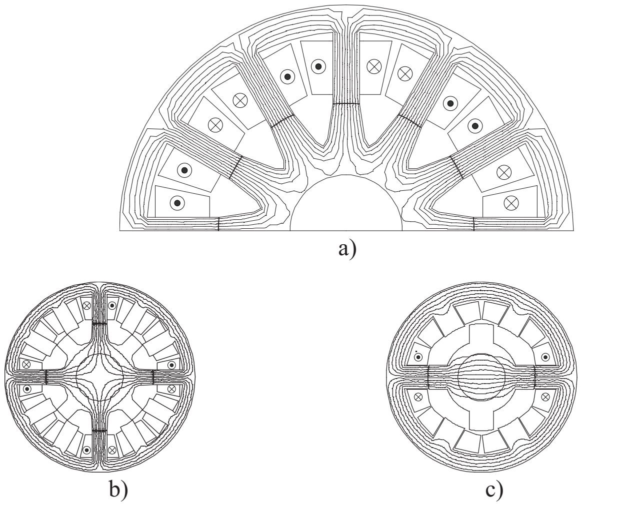

Fig. 11. a) The shorter magnetic lines in aligned rotor position in single phase 12/12 SRG topology, b) magnetic lines in three phase 12/8 SRG topology, c) magnetic lines in three phase 6/4 SRG topology

Single phase SRG have obviously the same number of stator and rotor poles. The windings on all the poles create one phase therefore they can be in series or parallel. Magnetic flux of the each pole is closed only by the adjacent poles and by very small part of the stator and rotor yokes. The magnetic lines are therefore shorter than those of three phase topology as it is seen in Fig. 11, a.

In addition, in multiphase topology the stator yoke must carry the flux also from the other phases, what results in the increasing of the flux density magnitude and hence the higher losses.

Table 2. The parameters of SRG with various number of phases and poles

Number of phases	m	1	1	2	2	3	4
Number of stator/rotor poles	N_s/N_r	6/6	12/12	4/6	12/16	12/8	8/6
Rotor pole pitch	α_{pr} (°)	60	30	60	30	45	60
Stator pole pitch	α_{ps} (°)	60	30	90	45	30	45
Stroke angle	ε (°)	60	30	30	15	15	15
Number of duty cycles	N	6	12	12	24	24	24
Fundamental frequency of the phase current	f_{iph1} (Hz)	300	600	300	600	400	300
Fundamental frequency of the rotor flux	f_{r1} (Hz)	300	600	50	100	100	50

In single phase SRG the magnetic flux waveform is triangular in the stator yoke as well as in the poles and to achieve the same magnetic flux density in the poles and yoke it is enough to have for yoke a half of the cross section area of the pole. In the operation above the basic speed it is necessary to excite in advance, it means before achieving the aligned position. The SRG develops at this moment a motoring torque, which is eliminated in the multiphase topologies by the other phase, or more phases. In this way the torque ripple in multiphase topologies is lower.

Therefore, in single phase topology this motoring torque causes higher noise and vibrations. To avoid negative mechanical influence on the prime mover, it is needed to ensure much higher moment of inertia of the prime mover in comparison with the SRG. The simulated output power of the single and multiphase topologies are shown in Fig. 12. They can be compared with regard to the topology three phase 12/8, which corresponds to the electrical power of investigated SR machine.

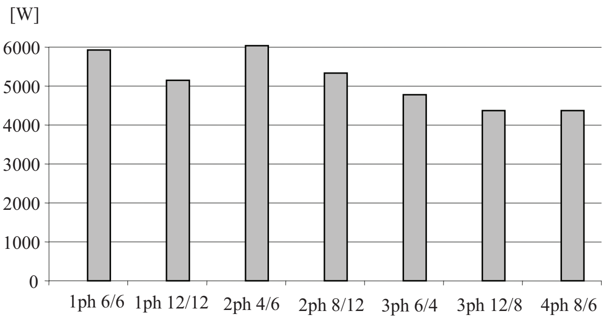

Fig. 12. The simulated output power of the single and multiphase topologies.

The number of turns for new topology (subscript 2) has been calculated on the base of equal winding losses belonging to the basic topology (subscript 1):

$$m_2 I_2^2 R_2 = m_1 I_1^2 R_1 , \tag{16}$$

$$m_2 I_2^2 \rho \frac{l N_2}{S_2} = m_1 I_1^2 \rho \frac{l N_1}{S_1} , \tag{17}$$

where m is phase number, ρ is relative electrical resistance of conductor, S is cross section area of conductor. If it is predicted that the medium length of turns is the same, it results in

$$N_2 = \frac{m_1 I_1^2}{m_2 I_2^2} N_1 \frac{S_2}{S_1} . \tag{18}$$

The cross section area of the conductor can be expressed by means of cross section area of the coil S_c, number of stator poles N_s, phase number m and number of turns per phase N as follows

$$S_1 = S_{c1} \frac{N_{s1}}{m_1 N_1} \tag{19}$$

or for new topology

$$S_2 = S_{c2} \frac{N_{s2}}{m_2 N_2}. \tag{20}$$

After introduction to the above expressions we get for the number of turns for a new topology an expression:

$$N_2 = N_1 \frac{m_1 I_1}{m_2 I_2} \sqrt{\frac{S_{c2} N_{s2}}{S_{c1} N_{s1}}}. \tag{21}$$

For example the single phase topology 6/6 can be realized as follows: N_2 = 204 turns in series, what means it can be 204 turns at each pole with current 30/6=5 A (30 A is maximal current) and the pole windings will be in parallel to the dc circuit or 204/6=34 turns per pole with current 30A and pole winding will be in series. Magnetomotive force is 6120 A, what is 3.15 times more in comparison with 1940 A per phase in basic topology. The highest power 6000 W achieves the single phase SRG 6/6 and two phase 4/6 topology, what is about 38% more than basic topology (three phase 12/8).

Conclusions

An optimal topology of SRG magnetic circuit from the point of view of achieved output power has been investigated. On the base of presented mathematical model the output power has been simulated for two kinds of single phase and five kinds of multiphase topologies. The results have shown that most suitable for SRG operation is single phase 6/6 topology and two phase 4/6 topology, which give 38% increasing in comparison with basic topology (three phase 12/8).

Acknowledgment

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This paper deals with comparison of the SRG output power with regard to the phase number and number of stator and rotor poles. An optimal topology of SRG magnetic circuit from the point of view of achieved output power is investigated by means of FE analysis. On the base of presented mathematical model the output power is simulated for two kinds of single phase and five kinds of multiphase topologies. Some measurements are carried out in motoring mode and compared with FEM investigations and simulations to verify mathematical model of SR machine. Ill. 12, bibl. 12, tabl. 2 (in English; abstracts in English and Lithuanian).

V. Hrabovcova, P. Rafajdus, M. Liptak. Fazių ir statoriaus bei rotoriaus polių skaičiaus įtakos besijunginėjančiojo generatoriaus išėjimo galiai tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 3(109). – P. 25–30.

Tirta, kaip besijunginėjančiojo generatoriaus išėjimo galia priklauso nuo fazių ir statoriaus bei rotoriaus polių skaičiaus. Pateikta magnetiniu požiūriu optimali grandinės topologija. Atliktas išėjimo galios modeliavimas. Il. 12, bibl. 12, lent. 2 (anglų kalba; santraukos anglų ir lietuvių k.).