The influence of control parameters on energy efficiency of switched reluctance generator for vehicle applications

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Abstract. In the paper, the possibilities of application of switched reluctance generators in modern variable-speed drives were discussed. The process of mechanical energy conversion into electric energy was discussed. Based on simulation and laboratory tests, output power profiles, efficiency profiles and profiles of ratio of output power to phase current were determined in the single-pulse mode. The authors showed that proper selection of control parameters allows the operation of the SRG with maximum power, maximum efficiency or maximum ratio of output power to phase current. Finally, conclusions concerning advantages of using SRGs in variable-speed applications were drawn.

1 Introduction

Due to the development of variable-speed applications and hence increasing demand for electrical energy, research on efficient, fault tolerant, compact and reliable generation systems are being conducted. In recent years, the intensified development of vehicles with hybrid and electric drives can be seen. Electric machines, which operate depending on the situation, among others, as a generator, are used in both of these types of drives. The development of these types of vehicles is a part of a global tendency to decrease negative impact of combustion engines on the environment. Despite strict emission standards, combustion engines will still have negative impact on the environment. Stricter emissions standards can only decrease but not eliminate a problem of exhaust emissions into the atmosphere. The vehicles with hybrid drives do not solve this problem, but they allow covering short distances only with electric drive. Only vehicles with electric drive alone allow eliminating exhaust emissions into the atmosphere. However, we should be aware that vehicles with hybrid or electric drives are not completely harmless for the surrounding environment. In hybrid vehicles, combustion engine drives electric machine which operates as a generator and charges batteries. In vehicles with electric drive, batteries are charged from the mains. In both electric and hybrid drives, part of accumulated kinetic energy of moving vehicle is converted into electric energy. It is possible when electric machine operates as a generator. Recently, systems for converting kinetic energy into electric energy

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during vehicle braking are used in many vehicles with combustion engines which are equipped with Start-Stop systems. Such vehicles are very often called semi-hybrid recently.

In vehicles with electric and hybrid drives and with Start-Stop systems, energy recovery during vehicle braking depends largely on the road conditions. During smooth deceleration or braking, energy recovery should occur at as high efficiency of kinetic energy conversion into electric energy as possible. Braking distance is very important while sudden stoppage of the vehicle is necessary. In this case, braking with classic mechanical brakes is very important. However, part of kinetic energy can be converted into electric energy in this case. Emergency braking process should be assisted as much as it is possible by electric machine. It means that converting of kinetic energy into electric energy has to be directed into obtaining as high braking torque as possible.

Various types of electric machines are used in above-mentioned solutions [2-4]. However, brushless motors with permanent magnets are currently most widely used. They are characterized by the highest efficiency of energy conversion and very small dimensions. High efficiency can be obtained by using high-energy permanent magnets but this solution has two main disadvantages. The first one is high price of permanent magnets and the second one is the source of origin of permanent magnets. Most of the well-known resources of rare-earth elements which are used in manufacturing of high-energy permanent magnets are in the possession of one of the Asian countries. Therefore, studies on alternative technologies of electric machines for above-mentioned applications should be conducted and switched reluctance machines could be one of them [5-7].

In the paper, generating operation of switched reluctance machine is analysed. The process of mechanical energy conversion into electric energy is discussed. Based on simulation and laboratory tests, the authors show that proper selection of control parameters allows operation of SRG with maximum efficiency, maximum power or maximum ratio of output power to phase current (P/I). Finally, conclusions concerning advantages of using SRGs in variable-speed applications are presented.

2 SRG-based energy conversion

Switched reluctance machines are categorized among machines with electronic commutation where classic commutator is replaced by dedicated power converter with control system. Fig.1a shows a structure of 8/6 switched reluctance machine (Fig.1a). The switched reluctance machines have a rotor without windings; they are concentrated only in a stator. The electromagnetic torque is produced by the tendency of alignment of stator and rotor. The rotor tends to the position where reluctance is the smallest.
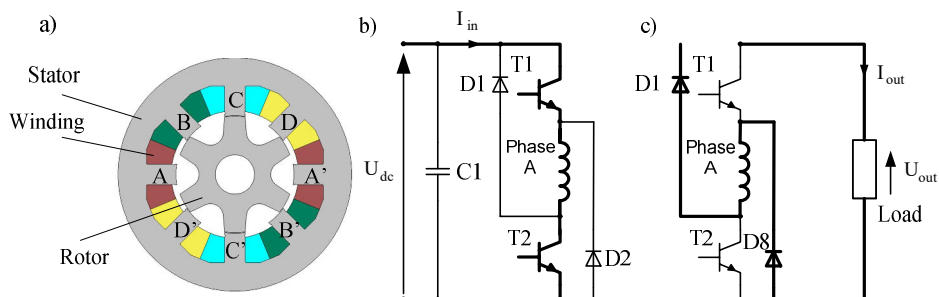

Fig. 1. a) A structure of the 8/6 switched reluctance machine, b) one leg of the power converter during excitation stage and c) during generation stage

Figs.1b and 1c show one leg of the power converter with marked directions of phase current flow at the excitation stage (Fig.1b) and at the generation stage (Fig.1c) [1]. In the

single-pulse mode, both switches are turned-on at the turn-on angle θ_{on}, current flows from the dc source and energy is stored in the magnetic field of the machine. Beyond the turn-off angle θ_{off}, both switches are turned-off and the energy provided by the prime mover through a shaft is converted into electric energy. Fig.2 shows idealised waveforms of phase back-EMF e_{ph} (Fig.2a), phase electromagnetic torque T_{eph} (Fig.2b), phase current i_{ph} (Fig.2c) and phase power P_{ph} (Fig.2d) in the single-pulse mode. The phase BEMF e_{ph} changes its direction after aligned position of rotor θ_a (Fig.2a). The sign of e_{ph} is determined by $dL_{ph}/d\theta$ and its amplitude varies with the rotor speed, so behaviour of phase current i_{ph} (Fig.1b) is determined by the relationship between e_{ph} and U_{dc}. The change of phase BEMF sign to negative also causes a change of a sign of the generated electromagnetic torque T_{eph} (Fig.1c). Switched reluctance machine starts to operate in a braking mode or in a generating mode (Fig.1c). It can be seen in Fig.1c that when turn-on angle is earlier than aligned position, electromagnetic torque is positive and machine operates in a motoring mode for a while. Output power in the switched reluctance generator is a function of supply voltage U_{dc}, speed n and control variables (θ_{on} and θ_{off}).
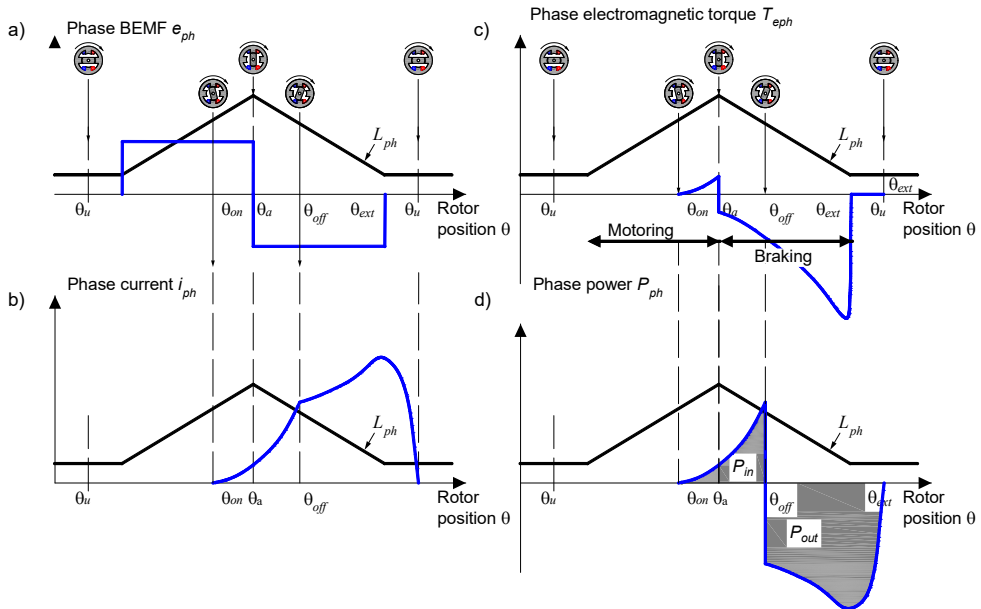

Fig. 2. Idealised waveforms of a) phase back-EMF e_{ph}, b) phase electromagnetic torque T_{eph}, c) phase current i_{ph} and d) phase power P_{ph} in the single pulse-mode

3 Results of simulations

In table 1, basic parameters of tested switched reluctance machine are presented.

Table 1. Basic parameters of the tested SRM.

Parameter	Value
Number of stator phases N_s	8
Number of rotor poles N_r	4
Rated voltage U_N [V]	24
Rated power P_N [W]	750
Rated speed n_N [rev/min]	3000

The simulation tests of the SRG were conducted based on nonlinear simulation model built in the Matlab/Simulink environment [8]. The influence of control parameters on properties of switched reluctance generator was determined based on the simulation model. Figs.3-5 show exemplary simulation results. Fig.3 shows dependence of average output power P_{outav} in the function of control parameters (turn-on angle θ_{on} and turn-off angle θ_{off}) at constant speed n=3000 rev/min and constant dc-link voltage U_{dc}=24V and with marked points of maximum power.
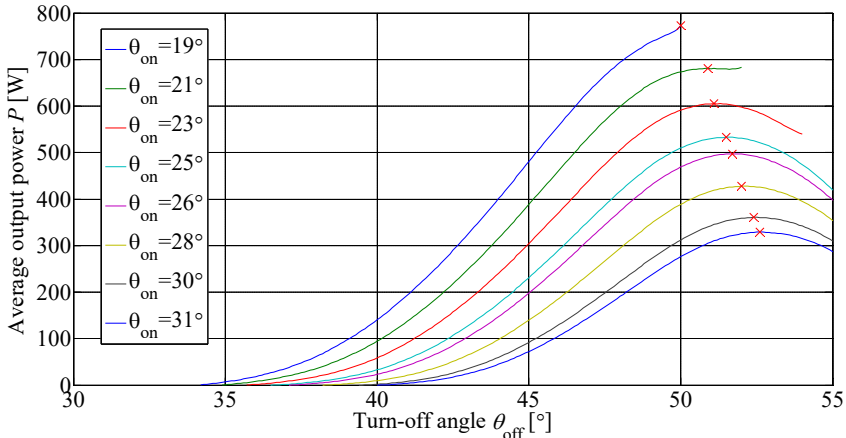
Fig. 3. The average output power P_{outav} vs. turn-off angle θ_{off} at θ_{on}=const, U_{dc}=24 V and n=3000 rev/min
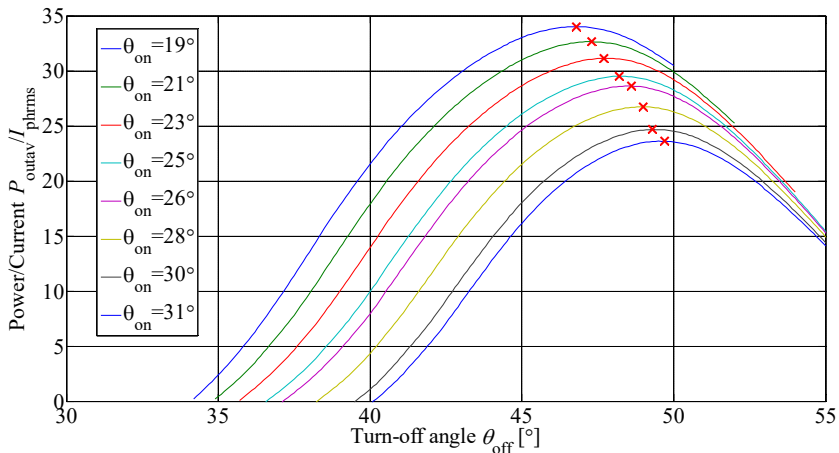

Fig. 4. The power/current ratio P_{outav}/I_{phrms} vs. turn-off angle θ_{off} at θ_{on}=const, U_{dc}=24 V and n=3000 rev/min

It can be seen from Fig.3 that selection of control parameters has to be dependent on value of required output power. However, other criteria should be taken into account when control parameters are selected. One of them is criterion of maximum efficiency. The second one is criterion connected with ratio of average output power to phase RMS current P_{outav}/I_{rms}. Fig.4 shows dependence of ratio P_{outav}/I_{rms} in the function of control parameters at n=3000 rev/min and U_{dc}=24V. When control parameters are selected to obtain maximum efficiency, output power is significantly limited. However, when control parameters are selected to obtain maximum output power, efficiency is noticeably lower. The selection of

control parameters to obtain maximum ratio P_{outav}/I_{rms} allows obtaining higher output power than for criterion of maximum efficiency. At the same time, efficiency of energy conversion is higher than for criterion of maximum output power. Fig. 5 shows dependence of average output power P_{outav} in the function of speed n. Control parameters were selected to obtain maximum values of average output power P_{outav} and ratio P_{outav}/I_{rms}.
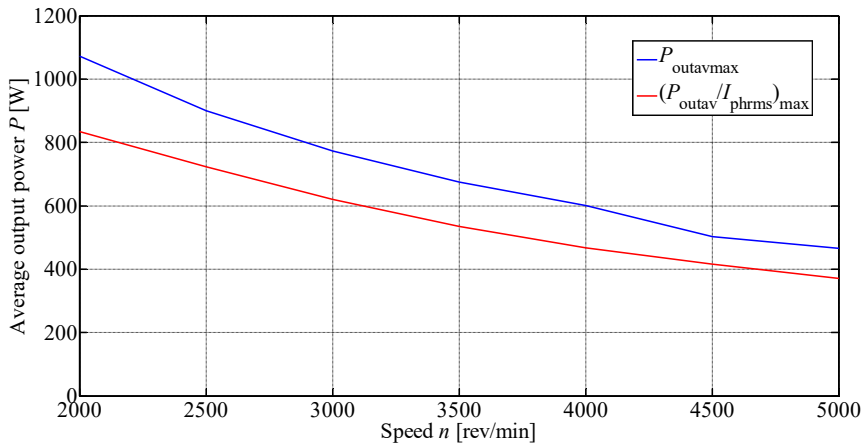

Fig. 5. The output power P_{outav} vs. speed n – simulation tests

The control with maximum ratio P_{outav}/I_{rms} gives 23% decrease of average output power.

4 Results of laboratory test

Fig.6 shows a schematic diagram of a laboratory setup. Yokogawa WT1600 digital power meter was used to measure all electric (current, voltage and power) and mechanical (speed, torque) parameters of the tested machine.
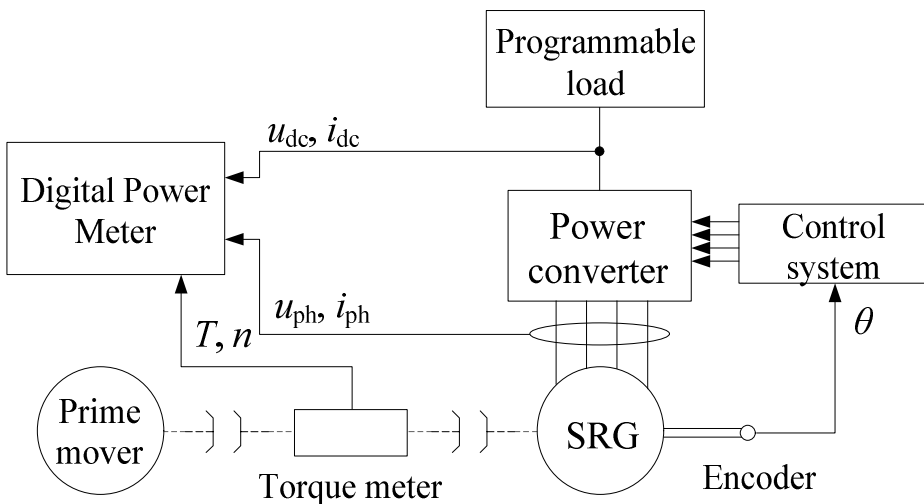

Fig. 6 A schematic diagram of the laboratory setup

In laboratory conditions, practical tests of control parameters influence on properties of switched reluctance generator were conducted. Fig.7-10 show results of laboratory tests. Fig.7 shows dependence of average output power P_{outav} in the function of control

parameters (turn-on angle θ_{on} and turn-off angle θ_{off}) at constant speed n=3000 rev/min and constant dc-link voltage U_{dc}=24V and with marked points of maximum power.
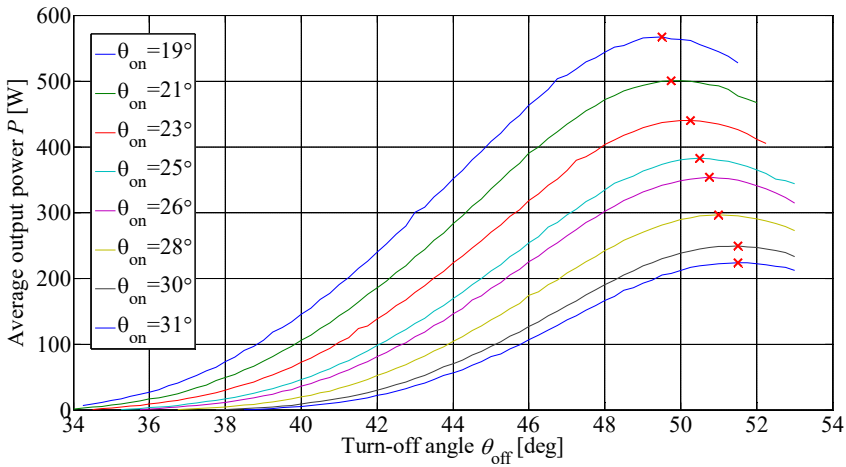

Fig. 7. The average output power P_{outav} vs. turn-off angle θ_{off} at θ_{on}=const, U_{dc}=24 V and n=3000 rev/min

Efficiency of energy conversion η in the function of control parameters (turn-on angle θ_{on} and turn-off angle θ_{off}) at constant speed n=3000 rev/min and constant dc-link voltage U_{dc}=24V was shown in Fig. 8.
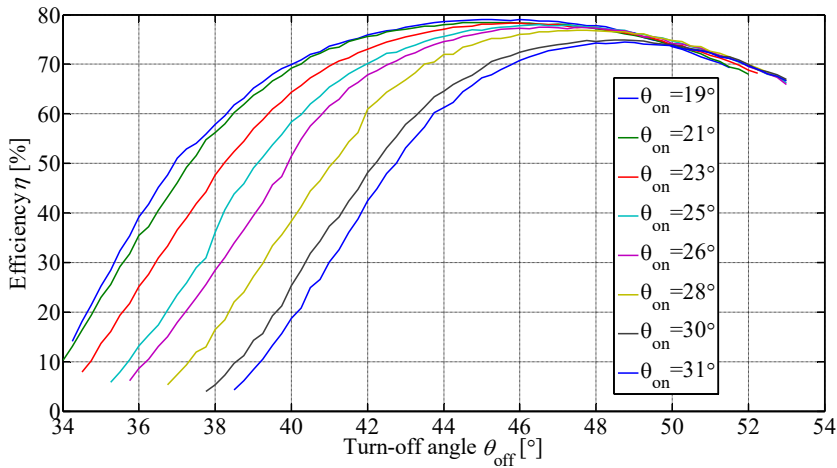

Fig. 8. The efficiency η vs. turn-off angle θ_{off} at θ_{on}=const, U_{dc}=24 V and n=3000 rev/min

Points of maximum efficiency was obtained at completely different control angles than points of maximum output power. Fig.9a shows dependence of average output power P_{outav} in the function of speed n where control angles were selected to obtain:

- maximum output power P_{outav},
- maximum ratio P_{outav}/I_{rms},
- maximum efficiency η.

Fig. 9b shows dependence of control angles (θ_{on} and θ_{off}) in the function of speed at which above mentioned criteria were obtained.
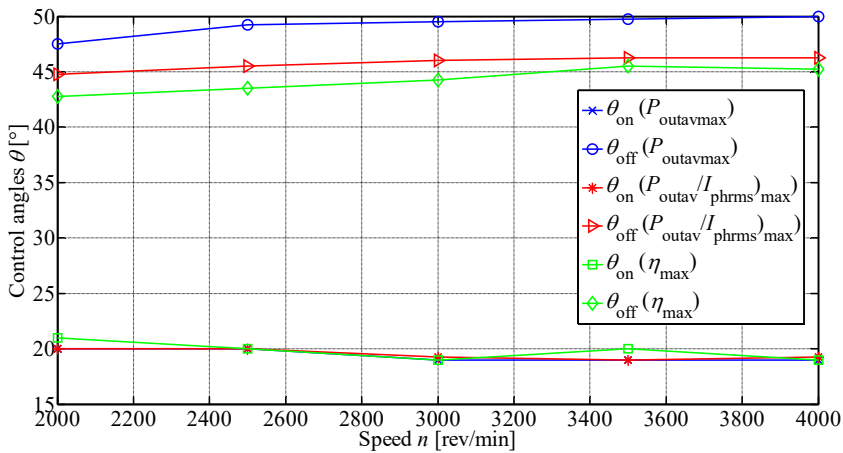
a)
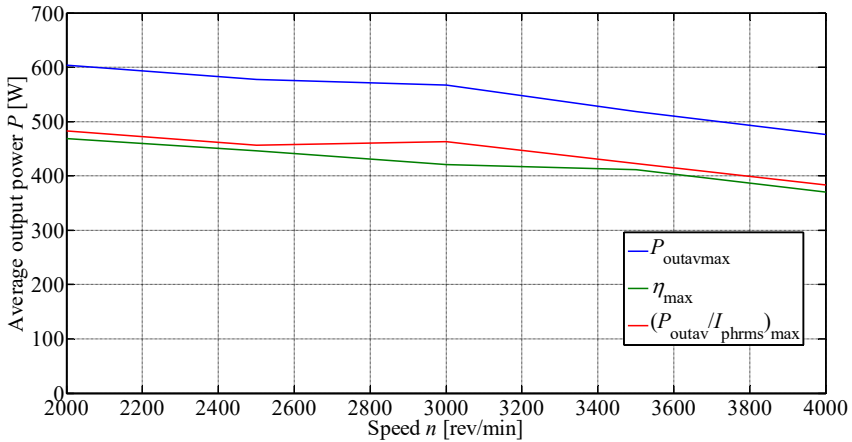
b)

Fig. 9. a) Control angles θ_{on}, θ_{off} vs. speed n, b) the output power P_{outav} vs. speed n – laboratory tests

Results of laboratory tests confirmed that control angles at which maximum power was obtained give lower efficiency of energy conversion, so this is not optimal control. Increase of efficiency is connected with decrease of generator output power.

5 Conclusions

The switched reluctance machines are an alternative technology for brushless machines with permanent magnets. The lack of permanent magnets allows their manufacturing in European market. Despite simple structure, control of SRG compared to other types of machines is more complicated. The control directed to obtain maximum output power causes decrease of energy conversion efficiency. However, this state can be used for emergency braking of vehicle when as high braking torque as possible is required. The control with maximum efficiency or maximum ratio P_{outav}/I_{rms} can be used when a vehicle

brakes smoothly or during typical generating operation i.e. wind turbine. During generating or braking operation, the control with maximum efficiency of energy conversion should be used for small powers and the control with maximum value of ratio $P_{\text{outav}}/I_{\text{rms}}$ should be used for medium powers.

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