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FAILURE MODE STUDY IN SWITCHED RELUCTANCE MACHINES IN THE GENERATOR MODE

ABSTRACT *Problem of the operation of a switched reluctance machine (SRM) in generator mode for normal and faulty electrical conditions is discussed in this paper. Cases of asymmetric work in SRM are described. Findings of simulation and experimental research are included and conclusions presented.*

Keywords: *switched reluctance machines, faulty electrical conditions*

1. INTRODUCTION

Switched reluctance machines fall into a category of electronically commutated electric machines. They are of simplified rotor design (there are neither windings nor magnets) and wide rotational speed setting range. They can be selected as an alternative solution for the drives where controlling of rotational speed is required. SRM's integrated in drive systems may be operated both in motor and generator modes (electric car drives, integrated starter/generator systems) or solely in the generator mode (e.g. wind turbines).

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The switched reluctance machine is capable of withstanding significant mechanical damage and continue operation while some failure modes persist. The failure modes in the machine operated as a motor due to external or internal factors have been subject to studies in [1-3]. Papers on failure modes at generator operated SRM's are scarce however. Selected failure modes in the SRM's at generator operation have been discussed in [4], but it was focused rather on voltage drops phenomena due to some specific application. Also selected failure modes for the generator operated SRM's have been discussed in [5].

The aim of this paper is to provide the findings obtained in the course of both simulation and laboratory research, pertaining to the generator operated SRM for the selected electrical failure mode cases. Failure modes at generator operated SRM's were categorized in this paper. Selected electrical failure modes in SRM's were studied based on the simulation tests. Simulation analysis was conducted on the basis of the field calculations as well as of the application of circuit simulation model in the Matlab/Simulink package environment. Harmonic content of the current waveforms was analyzed. The influence of electrical failure affecting the machine operation was discussed. Selected failure modes were verified in the laboratory. Conclusions were summarized.

2. CATEGORIZING FAILURE MODES IN SRM GENERATOR OPERATION

Similarly to the motor SRM operation, the failure modes at generator operation may be categorized as [2-3]:

- external,
  - supply circuit failure,
  - control circuit failures or errors,

- internal,
  - mechanical failure,
  - electric failure.

For the generator operation characteristic values are as follows: average supply current I_{dcav} and average output power P_{outav}. The average values are selected due to the nature of variability of the discussed values which is associated with the principles of the machine operation.

Discontinuities and short-circuit conditions in power and electronic circuits are among the supply system failures.

Three cases of failure modes indicated as follows, are discussed in this paper:

- failure mode I – discontinued winding of a phase in the machine,
- failure mode II – only half winding powered (only one pole winding),
- failure mode III – short-circuit in the winding of the pole of a phase.

Winding discontinuity (failure mode I) is a typical inner damage of electric origin. The machine in such state cannot continue its operation, but its output decreases proportionally to the number of lost phases. For the three-phase machine, it loses 33% of the original output, and for the four-phase machine – 25%. In this case the average supply current I_{dcav} and the output P_{out} of the machine both related to their rated values, one can find by calculating it from the following formula:

$$I_{\mathrm{dcav}} = \frac{k}{m} \cdot I_{\mathrm{dcavN}} \tag{1}$$

$$P_{out} = \frac{k}{m} \cdot P_{\mathrm{outN}} \tag{2}$$

where:

k – number of powered phases,
m – number of phases in the machine.

In the case when only a half of phase winding is powered (failure mode II), the machine is able to continue its operation, but the output generated by the machine depends on where its operating position is located in the mechanical characteristics. The faulty phase is of higher base speed than the others. In such case the total average output developed by the machine increases as the faulty phase generates higher value of output than it would at normal operation.

Similar situation one can find when the winding of a phase was short-circuited (failure mode III). In both cases it is reasonable to consider disconnection of the faulty winding due to possible drop in output developed in the range of lower speeds, significant increasing of copper loss as well as machine vibration and noise levels.

3. SIMULATION CALCULATIONS AND HARMONIC ANALYSIS FINDINGS

Simulation analysis was limited only to one machine type configured as 6/4. Figures 1 through 2 show the results of field calculation findings of flux-current-angle (ψ - i - θ) characteristics (Figs. 1a, b) as well as static self-induction factors $L_{\text{self}}(i, \theta)$ (Figs. 2a, b) for the normal operation of the machine and when only one pole of the winding is powered (failure mode II).

a) b)

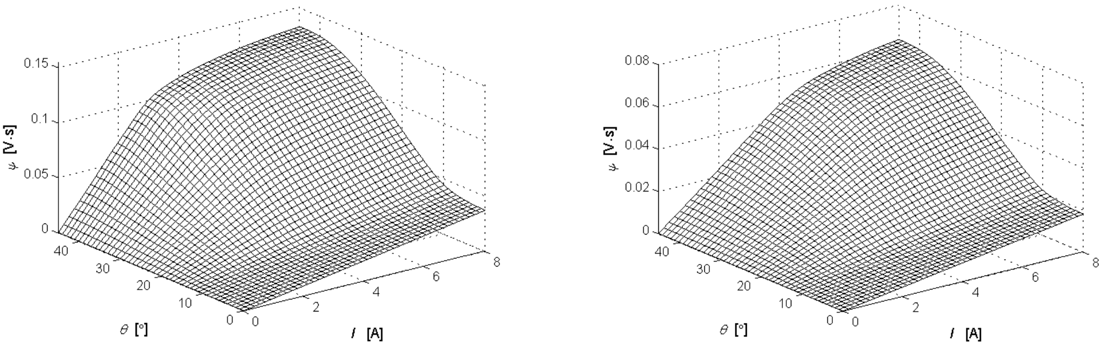


Fig. 1. Flux-current-angle characteristics
a) when entire phase is powered (normal operation) and b) when only one pole of the phase winding is powered (failure mode II)

a) b)

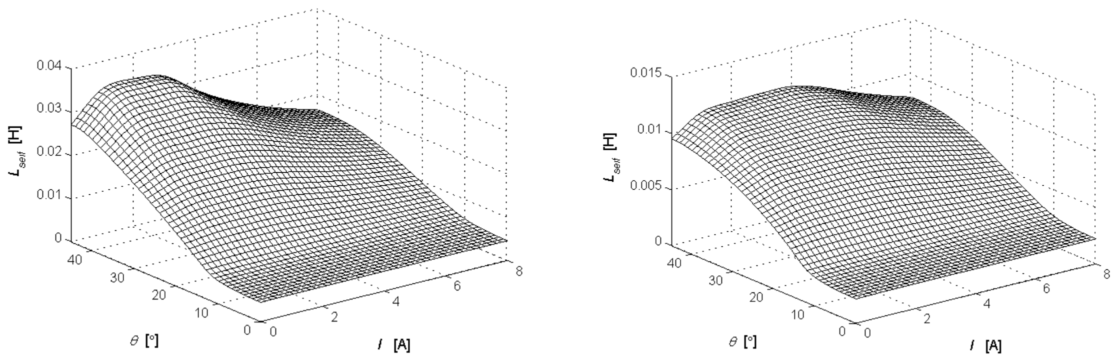


Fig. 2. Self-induction L_{self} versus current and the angle of rotation for
a) normal operation, b) when only one pole of the phase winding is powered (failure mode II)

Field calculation findings were utilized in designing simulation model in the Matlab/Simulink package environment. The calculations were performed with the assumption that voltage U_{dc} on the terminals of the machine is constant.

Figures 3 through 5 show the findings obtained for the normal operation of the machine (Fig. 3) as well as for two different cases of failure operation (Figs. 4 and 5). The figures show the waveforms of phase current i_{ph} (a), electromagnetic torque T_e (b) as well as the supply current i_{dc} (c) versus time, complemented with the harmonic decomposition (d). All the waveforms were obtained at the same rotational speed and control angles. Figure 3 shows waveforms at fully symmetric, normal operation. In the supply current waveform the 12-th harmonic and its multiples dominate. Figure 4 shows the waveforms of the phase currents i_{ph}, electromagnetic torque T_e and the power supply current i_{dc} when there is no power in a phase (failure mode I). Losing of any phase current makes both the source current i_{dc} and the resultant electromagnetic torque T_e to vary. The 4-th and 8-th harmonics found in the supply waveform attain magnitudes comparable to the 12-th harmonic resulting from the nature of switching cycles in the machine under consideration. The case of failure mode II, where only one half of the phase winding was powered, is shown in Figure 5. Higher current flows in the damaged phase. This varies shapes of both supply current i_{dc} as well as the electromagnetic torque T_e. Moreover, in this case of machine operation the 4-th and 8-th harmonics appear. However these are not dominant harmonics.

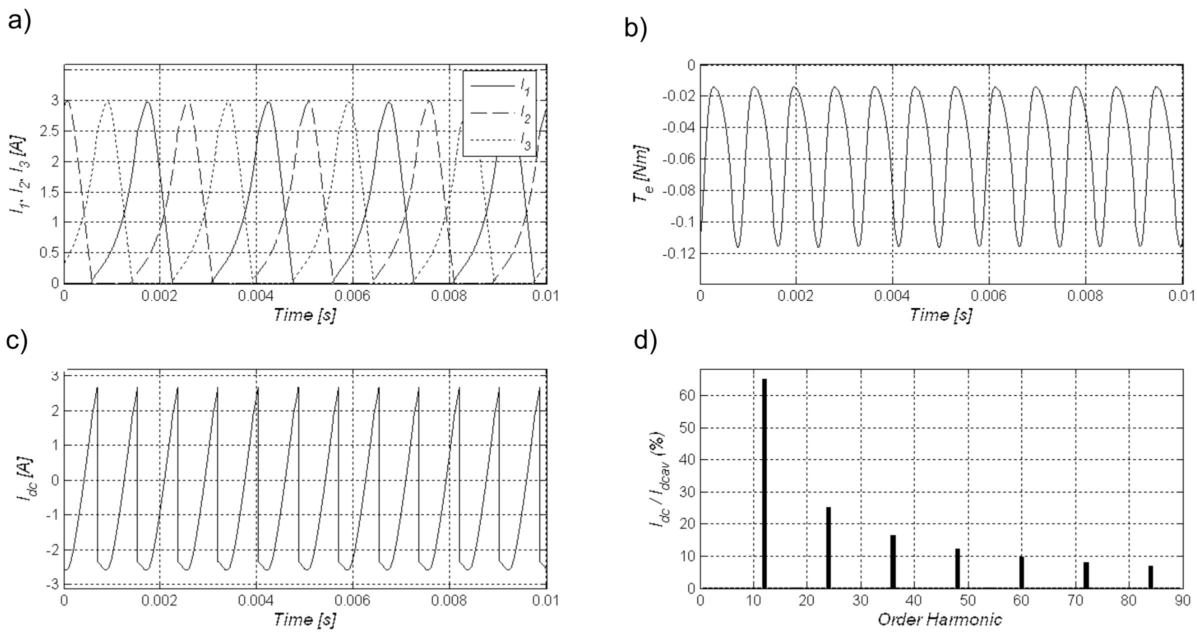


Fig. 3. Waveforms of phase currents

(a) electromagnetic torque (b) supply current (c) and harmonic decomposition of the supply current (d) at normal operation conditions

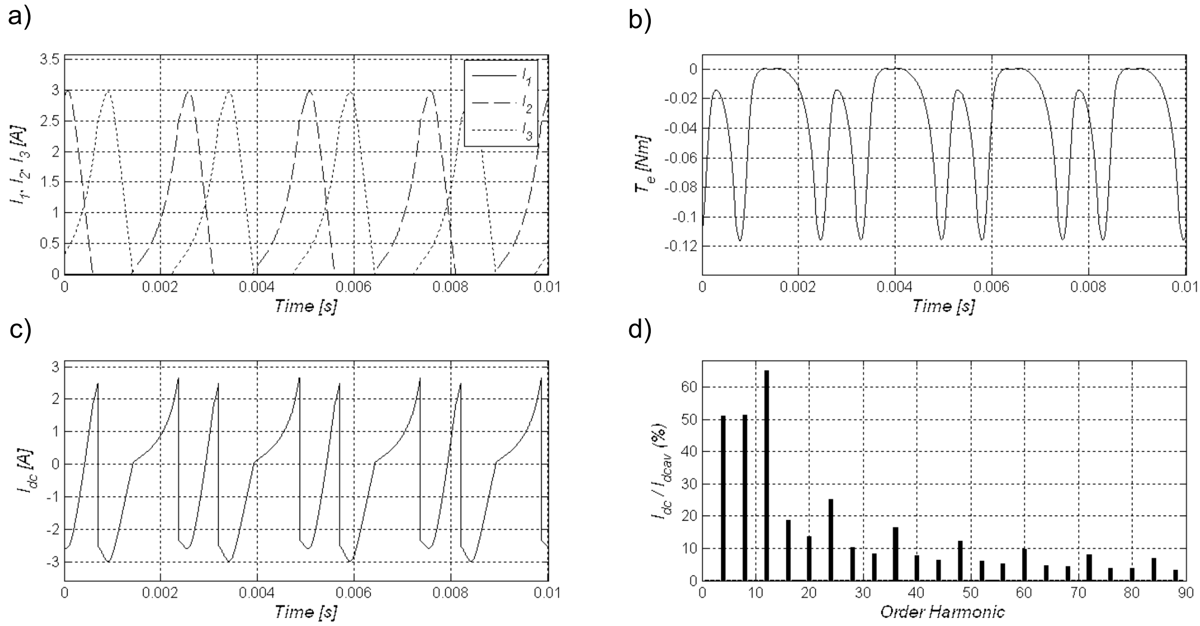


Fig. 4. Waveforms of phase currents
(a) electromagnetic torque (b) supply current (c) and harmonic decomposition of the supply current (d) - failure mode **I**

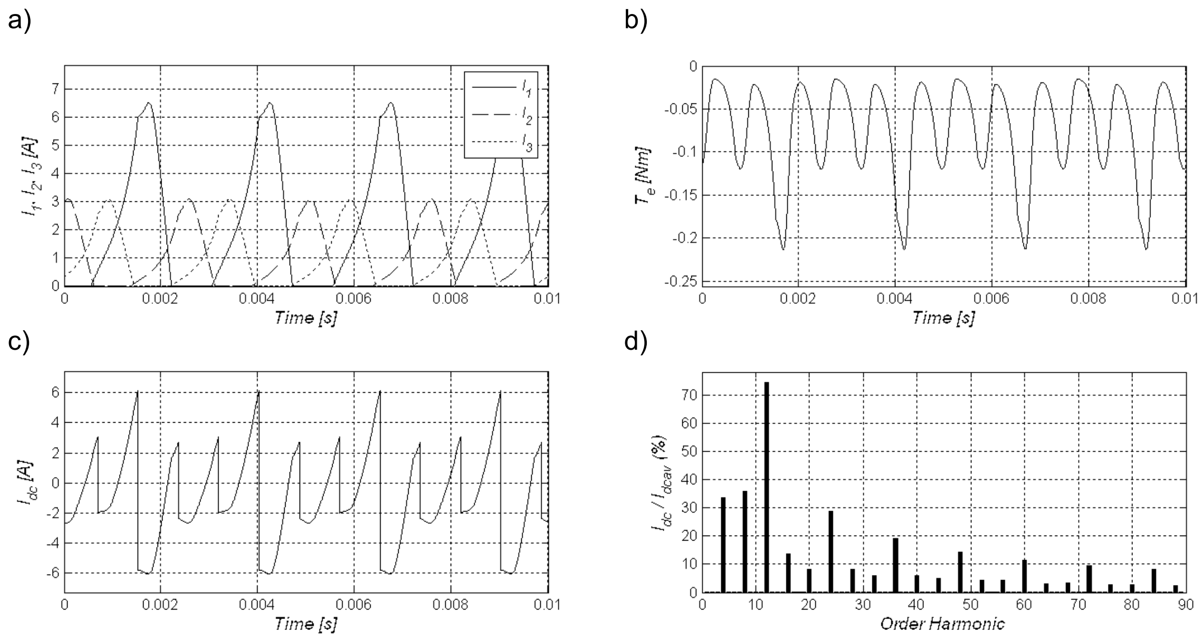


Fig. 5. Waveforms of phase currents
(a) electromagnetic torque (b) supply current (c) and harmonic decomposition of the supply current (d) - failure mode **II**

Figure 6 shows the average value of the supply current I_{dcav} versus speed of the machine for various conditions of the machine operation. Tests were conducted at identical control angle. Power loss in a phase (failure mode I) manifests itself by proportional drop of the average value of the supply current I_{dcav} according to relation (1). Once the fault is due to supplying power only to a half of the phase winding (failure mode II), one can notice increased average value of the supply current. Thus the output delivered by the machine does not decrease; on the contrary – it increases. The average value of current flowing through the faulty winding is much higher as compared to the other phases (Fig. 5). Once the short-circuiting occurs in one half of a phase winding, the average value of the supply current is also greater as compared to the conditions of normal operation. It increases less prominently as compared to the failure, due to the supplying power to only one half of the winding. The value of this current is higher than in the failure due to the supplying power to only one half of the phase winding at identical operating conditions.

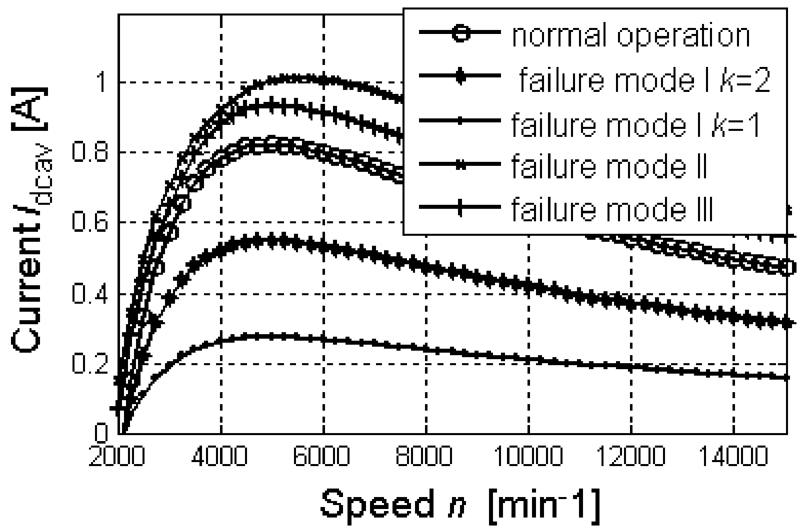


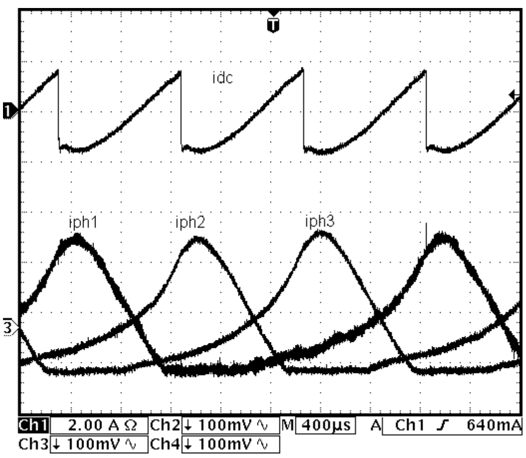
Fig. 6. Average value of the supply current I_{dcav} versus speed at various failure modes of operation

4. LABORATORY TEST FINDINGS

For selected failure modes attributable to the machine itself, testing was made and then compared with the machine operating at fully symmetric conditions. The power supply system was connected to the set of batteries. Figures 7 through 9 show the machine current waveforms in the fully symmetric case (Fig. 7), power loss in one phase (failure mode I – Fig. 8), circuit discontinuity in the winding of a pole and supplying power to the other portion (failure mode II – Fig. 9) as well as short-circuiting of one winding of the phase pole (failure mode III – Fig. 10). All waveforms were recorded at identical control angles (θ_{on} = 31° and θ_{off} = 75°) and the same speed, n = 4000 rpm.

At normal operating conditions, i.e. at control symmetry (Fig. 7) all current waveforms for each phase are similar one to another. No power in a phase manifests itself by changing the shape of the power supply current as well as proportional drop of its average value (Fig. 8). Similarly to the simulation tests, a damage due to loss of power in one pole winding, (Fig. 5) makes the current in the damaged phase to increase, which makes in turn the supply current to change the shape (Fig. 11). In the case of full short-circuiting in one pole winding (Fig. 8b-9), similarly to the loss of power in a pole winding, the current reaches significantly higher values than currents in defective phases. The shorted phase portion conducts the current of minor value (Fig. 9). When one compares the shapes of currents flowing in the short-circuited portion of a phase winding either all the phases are powered (Fig. 9) and when only the faulty phase is powered (Fig. 9b) one can notice, that both the shape and values of shorting current are independent from other phases of the machine. This supports the concept that goes that each separate phase of the machine can be considered as magnetically self-contained.

a)



b)

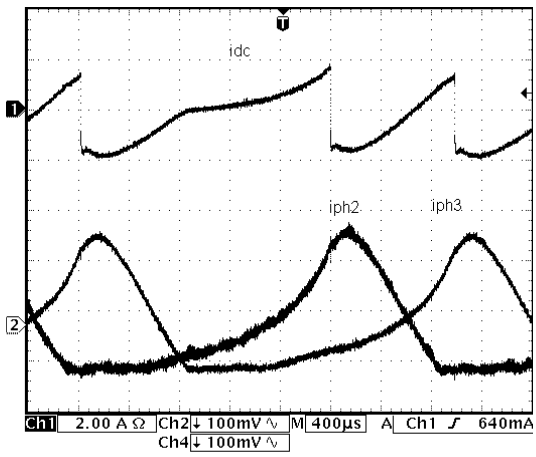
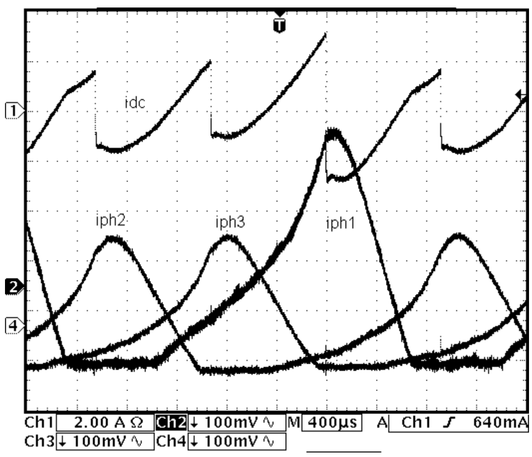


Fig. 7. Oscillogram of power supply current and phase current waveforms
a) at symmetric control – normal operation and b) when one phase is not power supplied – failure mode I

a)



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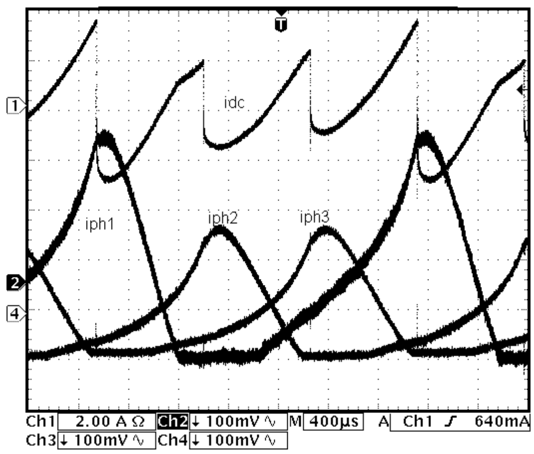
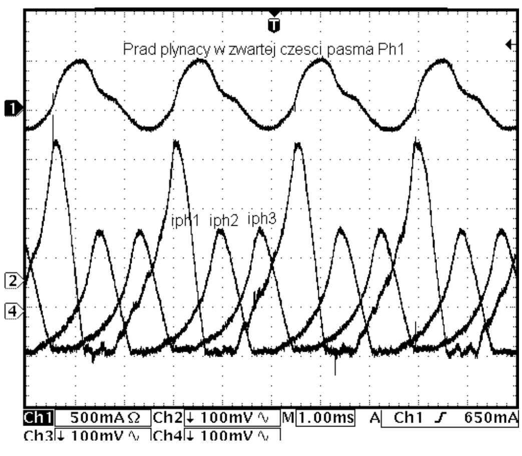


Fig. 8. Oscillogram of power supply current and phase current waveforms
a) when one half of the phase winding is powered – failure mode **II** and b) when one half of the phase winding is powered and the other short-circuited – failure mode **III**

a)



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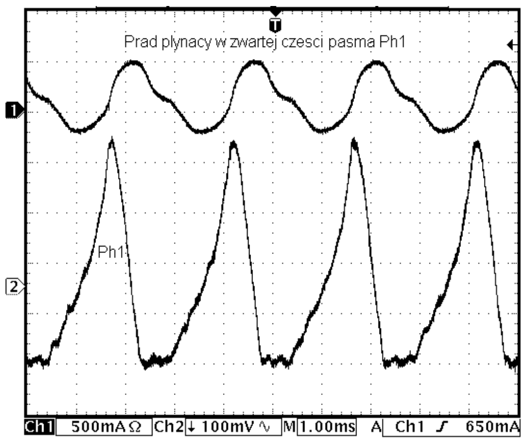

Fig. 9. Oscillogram of the current in the short-circuited winding and the phase currents when one half of the phase winding is powered and the other short-circuited – failure mode III and b) when one half of the phase winding is powered and the other short-circuited – failure mode III – the other phases are not powered

Figure 10 shows the average output in a phase for three cases, normal operation, supplying power to only one pole, supplying power to only one pole while the winding of the other pole is short-circuited.

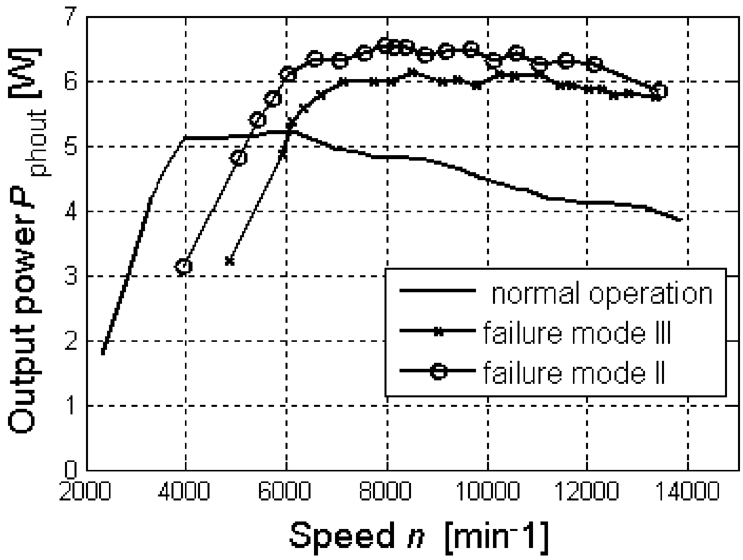

Fig. 10. Output power generated by a one phase versus speed for various failure modes

5. SUMMARY

The failure modes in the switched reluctance machine can be due to internal (the machine itself) and external (power supply system, control system) factors. When analyzing cases of faulty machines due to internal factors in the generator operating range, one can find prominent differences as compared to the motor operation. This mainly refers to the cases of short-circuiting of one pole of a phase. Thus average output increases in the region of higher speeds beyond the base speed of the faulty phase. However current in such faulty phase is of much higher value. This leads to the deterioration of the resultant efficiency of the machine as well as to increased risk of thermal failure of the other portion of the phase. The vibration and noise level generated in the machine is significantly increased due unbalanced magnetic pull.

Regardless of failure mode type, in the power supply current additional harmonics appear as compared to the symmetric control state. Operation of the drive system can be correctly diagnosed by harmonic analysis. If magnitudes of additional harmonics are comparable or higher than basic harmonic magnitude, this may indicate faulty machine.

Suitably adopted control system may ensure RMS current in faulty phase to maintain reduced to a minimum. The prolonged operation at such conditions is not recommended though, due to the risk for bearings to be damaged.

Machine fault due to complete loss of power in one phase or (m-1) phases, does not preclude continouing further motor operation.

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ANALIZA STANÓW AWARYJNYCH MASZYN RELUKTANCYJNYCH PRZEŁĄCZALNYCH W ZAKRESIE PRACY GENERATOROWEJ

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STRESZCZENIE *Maszyny reluktancyjne przełączalne (ang. Switched Reluctance Machines) zaliczane są do kategorii maszyn elektrycznych z komutacją elektroniczną. Charakteryzują się prostą budową wirnika (brak uzwojeń i magnesów) oraz bardzo szerokim zakresem regulacji prędkości obrotowej. W układach napędowych z SRM maszyny te mogą pracować zarówno w zakresie pracy silnikowej jak i generatorowej (napędy pojazdów elektrycznych, zintegrowane systemy rozrusznik/generator) lub tylko w zakresie pracy generatorowej (np. napędy elektrowni wiatrowych). Prosta budowa maszyny zapewnia bardzo dużą odporność na uszkodzenia elektryczne oraz możliwość kontynuowania pracy po wystąpieniu niektórych stanów awaryjnych. W rozdziale II dokonano klasyfikacji potencjalnych stanów awaryjnych przełączalnych maszyn reluktancyjnych. W pracy ograniczono się tylko do analizy wybranych stanów awaryjnych pochodzenia elektrycznego przełączalnej maszyny reluktancyj-*

nej 6/4 pracującej w zakresie pracy generatorowej takich jak przerwa w zasilaniu jednego z pasm maszyny (stan awaryjny I), zasilanie połowy uzwojenia pasma (stan awaryjny II) oraz zwarcie połowy uzwojenia (stan awaryjny III). Wszystkie stany awaryjne odnoszono do przypadku pracy w warunkach symetrycznych (warunki normalne). Dodatkowo założono, że maszyna pracuje w zakresie stałej mocy sterowana jednopulsowo z określoną prędkością obrotową i odpowiednimi kątami sterowania. Pracę podzielono na dwie części: obliczeniową (rozdział III) oraz weryfikacyjną (rozdział IV). Analizę symulacyjną prowadzono na bazie obliczeń polowych (rys. 1-2) oraz z zastosowaniem modelu symulacyjnego obwodowego w środowisku programów Matlab/Simulink. Na rysunkach 3-5 przedstawiono przebiegi czasowe prądów pasmowych i_{ph}, prądu źródła zasilającego i_{dc} wraz z rozkładem harmonicznych oraz momentu elektromagnetycznego T_e dla pracy normalnej maszyny oraz dla różnych przypadków pracy awaryjnej. Wszystkie charakterystyki uzyskano przy takiej samej prędkości obrotowej i kątach sterowania. Analiza harmoniczna prądu źródła zasilającego pokazuje, że w warunkach symetrii dominuje harmoniczna 12-ta i jej wielokrotności dla rozpatrywanej konstrukcji 6/4. W stanach awaryjnych pojawiają się dodatkowe harmoniczne 4 oraz 8. Analiza zawartości amplitud dodatkowych harmonicznych pozwala w wielu przypadkach określić rodzaj uszkodzenia. W warunkach laboratoryjnych dokonano pomiarowej weryfikacji analizowanych przypadków. Przykładowe przebiegi czasowe prądów przedstawiono na rysunkach 7-9. Na rysunku 10 pokazano zależność wartości średniej mocy wyjściowej jednego z pasm w funkcji prędkości obrotowej dla różnych przypadków pracy maszyny.