

# Fault Analysis and Excitation Requirements for Switched Reluctance Generators

Iqbal Husain, *Member, IEEE*, Arthur Radun, *Senior Member, IEEE*, and John Nairus

**Abstract**—Switched reluctance machines (SRMs) are a prime candidate for aerospace starter/generators and various automotive applications. The choice of SRMs for the starter/generator application is driven largely by the perceived reliability and fault tolerance of the machine and its electronics. An analysis of the switched reluctance generator's (SRG) faults and excitation requirements is essential to utilize the full fault tolerance capability of the machine in this application. Thus, research has been undertaken to identify, analyze and simulate the various fault modes of the SRG. This research included an investigation of the generator's excitation requirements with and without faults. The investigation makes it possible to determine the size of the excitation source required during the initial build up of the generator's output voltage and under fault conditions. The SR machine, controller, EMI filter, excitation source, and load were all modeled and integrated into a Matlab–Simulink model in order to analyze the SR generator system.

**Index Terms**—Excitation requirements, fault-tolerance, modeling of switched reluctance generators (SRGs), switched reluctance generators (SRGs).

## I. INTRODUCTION

THE SWITCHED reluctance machine (SRM) is unique in its operation as a generator in that it does not require permanent magnets or field windings on the rotor. The phase independence characteristic of the machine makes it extremely fault tolerant for critical applications. The absence of permanent magnets in SRMs eliminates the problem and fire hazard of the machine generating into a shorted winding compared to permanent magnet machines where one cannot turn-off the excitation. This unique feature of the SRM makes it ideally suitable for the aerospace integral starter/generator application being actively investigated by the Air Force for future aircraft. The SRM is also being investigated for various industrial and automotive applications. In the automotive industry, the SRM is a prime candidate for electronic power steering and anti-lock braking systems in conventional vehicles and for the main propulsion unit for electric/hybrid vehicles. The regenerative braking mode is desired to be an integral part of electric/hybrid vehicle drives, which provide further justification for fault analysis of SRGs.

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The fault analysis of SRM systems that have been published in the literature [1], [2] have dealt mostly with the fault tolerance and fault detection for the machine operated as a motor and not as a generator. During generating operation there is the added issue of the machine's excitation requirements compared to motoring operation because the SRM does not employ permanent magnets or a field winding for its excitation. Thus, it is important to investigate the excitation requirements for an SRM, particularly under faulted conditions. This paper will analyze the faults and the excitation requirements for an SRM operating in the generating mode. Although, most of the simulation results will be presented in the context of integral starter/generators for aerospace applications, the modeling and analysis approach is general and can be applied to any switched reluctance generator. The load fault performances of various alternatives to the three-phase, two-repetition EIS/G system are also analyzed for comparison. These alternatives included three-phase, three-repetition, and four-phase, two and three-repetition machines.

## II. SWITCHED RELUCTANCE GENERATOR

A switched reluctance machine (SRM) is operated in the generating mode by positioning phase current pulses during periods where the rotor is positioned such that the phase inductance is decreasing. This occurs immediately after the rotor and stator poles have passed alignment. Normally, in this generator mode, the machine obtains its excitation from the same voltage bus that it generates power to. Typically, a phase is turned on before a rotor pole aligns with that phase, drawing energy from the dc bus to excite the phase. Once the rotor pole passes alignment with the phase's stator pole the winding is disconnected from the dc bus. It then generates into this same bus through suitably connected diodes. The work done by the mechanical system to pull the rotor poles away from the stator poles is returned to the dc bus. The dc bus returns the excitation energy plus additional generated energy. The control key is to position the phase current pulses precisely timed with the rotor position relative to the phase's stator poles in order to maximize the efficiency and to reduce the stresses on the power electronic converter. The phase current pulses during generating are, in fact, the mirror images of the phase current pulses during motoring around the aligned position [3]. Typical phase currents in an SRM are shown in Fig. 1.

With SRMs, multiple channel generating systems can be built by repeating the basic stator and rotor pole arrangements. For example, a 2-channel, 3-phase machine can be built using a 12/8 pole configuration, which is 2-repetitions of the basic 6/4, 3-phase machine. Structures for 2-repetition and 3-repetition, 3-phase machines are shown in Fig. 2. The machines are wound such that, with the independent phase nature of the SRM, they

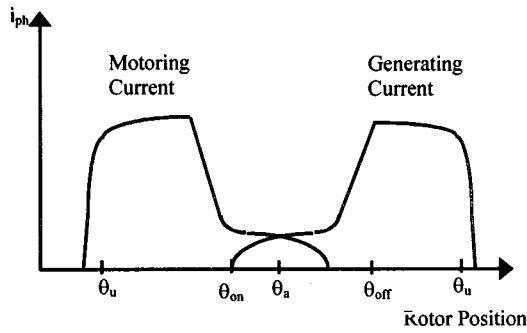


Fig. 1. Phase currents in an SRM ( $\theta_{on}$ ,  $\theta_{off}$ , shown are for the generating mode).

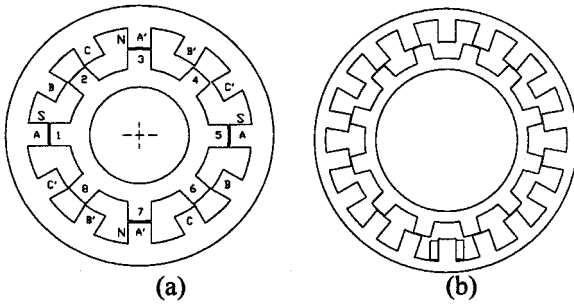


Fig. 2. Cross-sections of three-phase SR machines: (a) 12/8, 2-repetition (2-channel) structure; (b) 18/12, 3-repetition (3-channel) structure.

behave like two or three separate 3-phase machines. It is the independent phase nature of the SRM that allows a single machine to supply power to two (or more) separate, independent, and presumably differently loaded output buses.

The switched reluctance generator is typically operated in the constant power region of the torque-speed characteristics of the machine. In this region, the machine operation is limited to the single pulse mode, where the phase switches turn on (at  $\theta_{on}$ ) and turn off (at  $\theta_{off}$ ) only once per cycle. The higher machine speeds in this mode also cause the back-emf (BEMF) to be significant and is often higher than the dc bus voltage. The SRM can generate at lower speeds, but it would then be limited to a constant torque capability rather than the constant power capability required of a generator.

One channel of a switched reluctance generator including its power electronic converter, EMI filter and “diode-ORed” excitation source is shown in Fig. 3. The power electronics is the two switch, two diode per phase classic converter topology. A resistive load is assumed at the output of the generator.

The terminal phase voltage of an SRM is given by

$$V_{dc} = iR_{ph} + \frac{d\lambda}{dt} = iR_{ph} + \frac{\partial\lambda}{\partial i} \frac{di}{dt} + \frac{\partial\lambda}{\partial\theta} \omega_m$$

$$\Rightarrow \frac{di}{dt} = \frac{V_{dc} - iR_{ph} - \frac{\partial\lambda}{\partial\theta} \omega_m}{\frac{\partial\lambda}{\partial i}}$$

where

$$R_{ph} \quad \text{phase winding resistance}$$

$$(\partial\lambda/\partial\theta)\omega_m \quad \text{back-EMF (BEMF).}$$

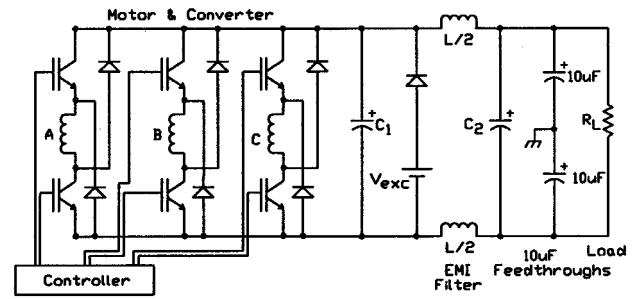


Fig. 3. Standard switched reluctance generator system.

The average generated current for a given set of  $\theta_{on}$  and  $\theta_{off}$  angles is proportional to the bus capacitor voltage and can be written as

$$i_{av} = k(\theta_{on}, \theta_{off})v_c = \frac{v_c}{R_k}$$

where  $k(\theta_{on}, \theta_{off}) = 1/R_k$  is a proportionality constant which depends on  $\theta_{on}$ ,  $\theta_{off}$ , machine speed  $\omega_m$ , and the bus capacitor voltage  $v_c$ . Here, the EMI filter has been neglected and an equivalent capacitor  $C$  is assumed in parallel with  $R_L$  across which the bus voltage  $v_c$  appears. The following relation governs the bus capacitor voltage

$$\frac{dv_c}{dt} = \left( \frac{1}{R_k C} - \frac{1}{R_L C} \right)$$

where  $R_L$  is the load resistance.

For fixed  $\theta_{on}$  and  $\theta_{off}$  angles, if  $R_k$  is less than  $R_L$ , which would be the case for lighter loads, the bus capacitor voltage would gradually increase and cause instability. On the contrary, if  $R_k$  were greater than  $R_L$ , which would be the case for heavier loads, the bus voltage would collapse to zero. Therefore,  $\theta_{on}$  and  $\theta_{off}$  angles are continuously adjusted in the feedback control loop, regulating the generator output voltage  $v_c$ , for regular and lighter loads so that  $R_k$  equals  $R_L$  on the average.

The “diode OR” excitation source  $V_{exc}$ , shown in Fig. 3, supplies the initial excitation current and the excitation current during and after a load fault. The diode blocks the generated current from going into the excitation source. Once the bus voltage builds up above the source excitation voltage, the diode isolates the initial excitation and fault source from the system and the machine draws its excitation current from the dc bus into which it generates.

During a load fault, when  $R_L$  is too small, the angles  $\theta_{on}$  and  $\theta_{off}$  would saturate to the maximum possible difference among them due to the control action of the feedback loop.  $\theta_{on}$  and  $\theta_{off}$  would then become fixed and the generator output voltage  $v_c$  would collapse to zero. The SR generator will not be able to recover after the fault is cleared unless battery or other excitation source supports the generator output bus. The question that arises next is how big an excitation source would be required for the starter-generator system. This paper presents an analysis and simulation results to determine the excitation requirements under normal and various faulted conditions.

### III. FAULT ANALYSIS

The location of faults in a SR generating system can be both internal and external to the machine. The faults occurring within

the machine, such as armature phase short or open faults are referred to as internal faults. The faults occurring in the external units, such as those in converters, excitation source or in the load are referred to as external faults. Descriptions of the internal and external faults are given first. Next, the results obtained from simulation of the faults based on the Simulink integral starter/generator model will be presented.

The internal faults can be classified as the following.

- 1) *Armature Phase Open*: The phase winding in a machine opens due to manufacturing defects or burnout of a weak link within the winding. The opened phase stops generating power into the dc bus. The controller increases the demand from the healthy phases to maintain the power generation. The healthy phases can supply power up to the limit of each phase. The output voltage ripple would increase, since generation is no longer as uniform as the pre-fault situation.
- 2) *Armature Phase Short*: Insulation failure in one of the phase windings may cause the phase to be completely or partially shorted. The partial phase winding effect depends on the number of turns shorted out. The short circuit will cause the converter switch to fail or a fuse in series with the winding/switch to blow depending on its power rating and short circuit current.

A partial list of possible external faults is given below. Only the external faults on this list have been investigated.

- 3) *Converter Switch Open*: When a converter phase switch fails open, it does not lead to any catastrophic failure, but stops supplying excitation current to the corresponding phase winding, and hence, one phase stops generating any power. Stopping the gate signals to the failed converter switch will simulate the situation. This will not be a common fault as semiconductors normally fail short.
- 4) *Converter Switch Short*: A phase winding receives uncontrolled excitation current when its corresponding converter switch fails short. Supplying gate signals to the faulted switch all of the time, simulates this scenario.
- 5) *Load Fault*: The load fault can occur for a variety of reasons. Whatever their cause, all load faults lead to fault currents into the load. Reducing the output load resistance simulates the load fault.

#### IV. MODELING OF STARTER/GENERATOR AND FAULTS

##### A. Generator Modeling

The nonlinear characteristics of a SR machine can be modeled either by using tables of flux-angle-current characteristics obtained from measurements or analytical expressions developed in [4]. The analytical expressions of [4] were used in the simulation. The model results match the experimental data very closely for a series of experiments that were conducted.

The analytical machine model, the output voltage controller model of [5], the diode-or model for the excitation source, the EMI filter of Fig. 3, and a resistive load model were incorporated into a Matlab–Simulink model. The Matlab–Simulink model was used to simulate the SR generating system with various fault conditions.

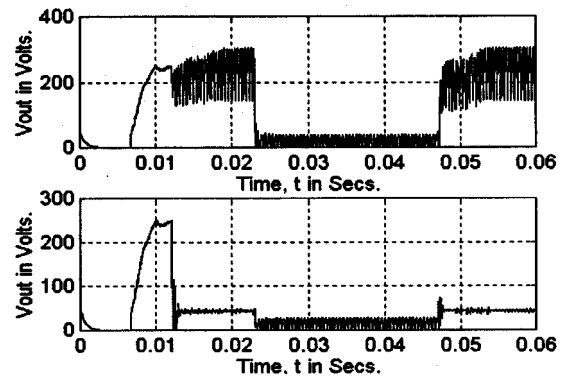


Fig. 4. Output voltage waveforms for phase winding short fault (top trace) and converter switch short fault (bottom trace).

##### B. Fault Modeling

The SR generator fault modes listed above were introduced into the basic Matlab–Simulink SR generating system model one at a time. The machine used in the simulations was the external integral starter/generator (EISG) machine. This is a 12/8, 2-channel, 250 kW, 22 000 rpm machine for which substantial data is available [6], [7]. The excitation source voltage was 50 V.

#### V. RESULTS OF FAULT ANALYSIS

##### A. Winding and Converter Faults

Simulation of the SR generator system shows that the SR generator is able to maintain its output voltage in the presence of a phase winding open or short fault, or in the presence of a phase switch open fault. In each case it is assumed there is no load fault. If there is only a load fault the output voltage decreases to a relatively small value and the SR generator system draws its excitation power from the excitation source through the OR-ing diode as expected. When a load fault is superimposed on a phase fault, the excitation power is again drawn from the excitation source through the OR-ing diode.

The output voltages for phase winding short and converter switch short faults are shown in Fig. 4. The step input of  $V_{out} = 270$  V is commanded at 5 ms, and the internal or external faults occur at 12 ms. Next, a load fault occurs at 23 ms. This load fault clears at 48 ms with the SR generator system operating thereafter with just the no-load fault. In the case of a complete phase winding short fault, the voltage ripple increases significantly although the voltage is maintained well above 50 V with a mean value of essentially 270 V. Energy is not drawn from the excitation source unless there is a load fault, which occurs at 23 ms. On the other hand, the phase-switch short results in an abnormally high value of source excitation currents, which would lead to catastrophic failures.

Phase freewheeling diode failure modes were not simulated, since these failure modes lead to short circuit conditions or catastrophic failures unless each IGBT current is sensed and the IGBTs are turned off when these failure modes occur. If this is done, the phase freewheeling diode failure reduces to a phase open fault. After a single OR-ing diode fail short (the most common), the SR generator continues to operate normally though it will not be able to clear a load fault (double failure).

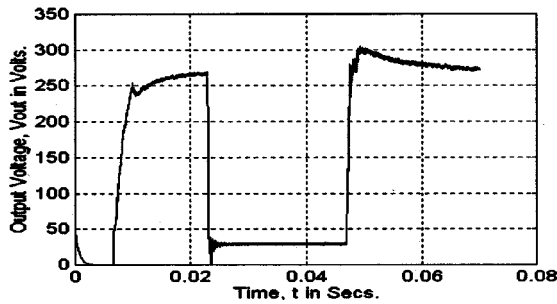


Fig. 5. Output voltage for a load fault.

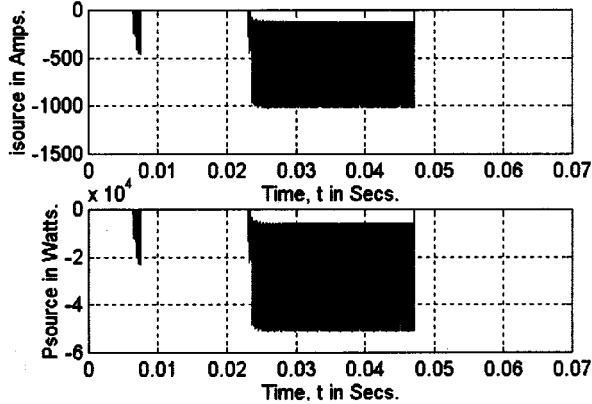


Fig. 6. Source current and excitation power required during start-up and faulted condition.

### B. Load Faults

Load faults are important for any generator system, since the generator system must be able to clear these faults by blowing fuses or tripping circuit breakers. Load faults are of particular concern for SR generators because of the SR generator's unique manner of excitation. The output voltage for the EIS/G for a load fault that occurs at 23 ms and cleared at 48 ms is shown in Fig. 5. The output voltage during fault collapses to 35 V. The phase current reaches 1400 A (peak) from its normal 900 A (peak) during the fault condition.

### C. Excitation Requirements

The excitation source power requirements were determined for each of the fault conditions introduced in the Simulink model. Load faults were superimposed on top of the phase or switch faults as shown in Fig. 4 to find the excitation requirements under these severe fault modes. Two point failures are of low probability and are normally not considered.

Excitation source current and excitation power required for the EISG is shown in Fig. 6. An excitation source of 50 kW capable of supplying 1000 A is required to sustain the load fault.

The excitation power required under various degrees of load fault was investigated by changing the load resistance gradually from its nominal value of 0.445  $\Omega$ . The results are presented below in Table I.

## VI. FAULTS WITH ALTERNATE MACHINES

The load fault analysis method presented above was extended to study the fault performance of SR generator systems that

TABLE I  
EXCITATION CURRENTS AND POWER REQUIREMENTS UNDER LOAD FAULTS

Load Resistance, RL	.1 $\Omega$	.05 $\Omega$	.02 $\Omega$	.01 $\Omega$	.001 $\Omega$
Load Current (peak) (Amps.)	870	860	1490	1950	2750
Load Current (average) (Amps.)	805	830	1450	1860	2650
Excitation Source Current (peak) (Amps.)	990	740	1000	1050	1120
Excitation Source Power (peak) (kW)	49.5	37kW	50	52.5	56

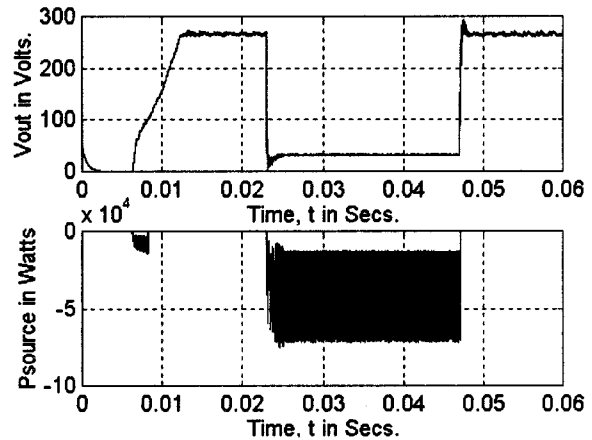


Fig. 7. Output voltage and source excitation power for a three-phase 3-repetition SR generator.

are alternatives to the EISG. The objective is to observe the fault performance of these alternatives, as measured by output power quality, and to compare with the results of the EISG. Three-phase machines with three repetitions, and four-phase machines with two and three repetitions were designed using the guidelines provided in [4] and [8].

### A. Alternate Machine Designs

The design constraints and limits, as well as the magnetic materials for the alternate configurations, were kept as close as possible to the 3-phase, 2 repetition EIS/G system. The following design guidelines were used.

*Design Constraints:* Rated Speed = 22 224 rpm, Corner Speed = 16 352 rpm, Maximum Power = 330 kW, Rated Power = 250 kW, dc Link Voltage = 270 Vdc.

*Design Limits:* Maximum Rotor Hoop Stress = 40 400 psi, Rms Current Density = 1254 A/cm<sup>2</sup>, Maximum Average Rotor Torque Density = 70 000 N-m/m<sup>3</sup>, Power Factor = 0.45, Efficiency = 0.95.

### B. Fault Simulations

Output voltage and excitation power with and without load faults for the three-phase and four-phase machines with a simulated load fault are shown in Figs. 7–9.

The 4-phase designs require less excitation power from the source for initial voltage build-up, but more during load faults. The fault load was the same for 3-phase and 4-phase, 2-repetition and 3-repetition designs. The simulations were performed

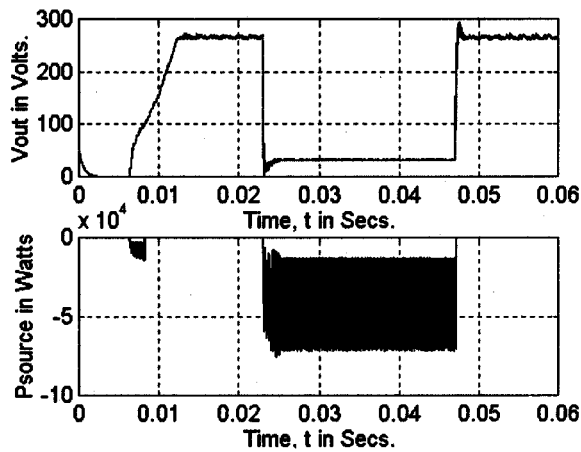


Fig. 8. Output voltage “V<sub>out</sub>” and source excitation power “P<sub>source</sub>” for the 4-phase, 2-repetition switched reluctance generator.

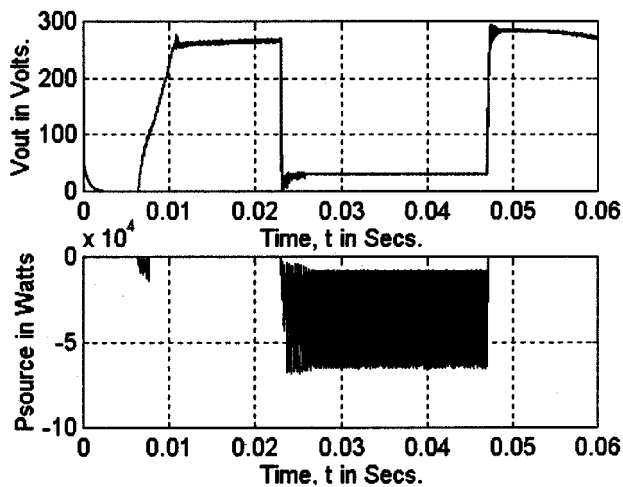


Fig. 9. Output voltage “V<sub>out</sub>” and source excitation power “P<sub>source</sub>” for the 4-phase, 3-repetition switched reluctance generator.

TABLE II  
EXCITATION SOURCE POWER REQUIREMENTS FOR ALTERNATE CONFIGURATIONS

Machine Configuration	3-Phase, 2-Repetition	3-Phase, 3-Repetition	4-Phase, 2-Repetition	4-Phase, 3-Repetition
	% of Channel Power	% of Channel Power	% of Channel Power	% of Channel Power
During Start-up	12%	18%	7%	9%
During fault	30%	47%	39%	59%

on a per channel basis and the results given in Table II are also on a per channel basis. The percentage excitation requirements for 3-repetition designs are more, although the power requirements are close. The airgap for the 3-repetition designs should

be proportionately reduced to minimize the excitation requirements. However, airgap was kept at 20 mil for all the designs considering manufacturing limitations.

VII. CONCLUSION

This paper presents the results of a series of simulation studies performed to determine the effect of faults on the operation of SR generators and on their excitation requirements. SR generator systems studied included those based on three-phase and four-phase machines. The excitation requirement for initial voltage build-up in the EIS/G is 12% of the delivered power, while for a load fault condition the power requirement is 30% in one channel. The excitation requirement for initial voltage build-up increases as the number of repetitions increase, but decreases with four-phase machines. The excitation requirements for voltage build-up are 18% for three-phase, 3-repetition, 7% for four-phase, 2-repetition, and 9% for four-phase, 3-repetition SR starter/generators. However, four-phase machines have higher excitation requirements under load fault conditions compared to three-phase machines.

Simulation showed that the SR generators are able to maintain its output with a single phase-short and a single phase-open fault condition. The SR generators are also able to maintain its output with a converter switch-open fault in one phase leg.

The Matlab-Simulink system models developed and used in this research can be conveniently used for system performance evaluation including fault conditions. An SR designer/investigator can adopt the methods presented here and apply to his/her own application fairly quickly.

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