# Operation of Separately Excited Switched Reluctance Generator

**Mahmoud S. Abouzeid** **Yasser G. Dessouky**
**Department of Control and Electrical Engineering**
**College of Engineering Studies and Technology**
**Arab Academy for Science and Technology**

**Abstract**

Switched reluctance machine proved to be an adequate variable speed drive suitable to different domestic and industrial applications. Its performance is still to be investigated in the generation mode, where it needs to be excited via the same single sided windings of the stator. In this paper, the operation of the switched reluctance generator will be laboratory tested and evaluated when the machine is driven by a variable speed DC shunt motor.

## 1. Introduction

Switched reluctance machine has been widely used as a variable speed drive since the late 70th. It showed great capability compared with similar drives[1]. Due to the singly excitation of the machine, it is possible to generate electric energy directly through the stator winding. Operating the switched reluctance machine as a generator necessitates current excitation in the stator winding once the mechanical energy is supplied to the rotor via a primover. Applied torque can be transferred to output electric power and delivered to any electric load connected to the switched reluctance machine terminals.

The excitation of the stator winding is done periodically and for limited intervals while the output electric energy is delivered to the load continuously even during the excitation periods through a capacitor filter. The excitation is triggered based on the rotor position using a transducer which does not depend on the primover speed. That means the possibility of driving the machine using different types of variable speed drives such as wind turbine[2]. Figure 1 illustrates the block diagram of the whole laboratory set-up used to operate the switched reluctance generator (SRG).

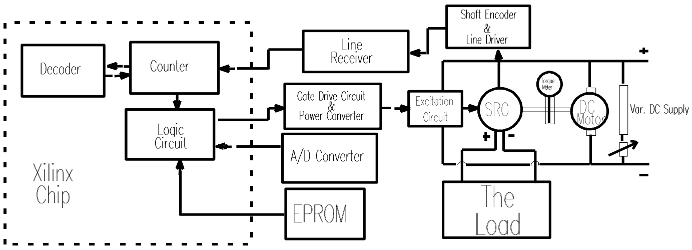


Figure 1. The SRG main components

## 2. System Description

In order to run the SRG, a primover, excitation and control circuits are needed. The primover can be either a variable or constant speed drive. In case of variable speed drive, the control circuit adjusts the appropriate excitation current switched to the SRG as will be explained in the next section. The speed range for the SRG chosen in this work is from 1000 rpm to 2000 rpm, so a dc shunt motor is suitable to drive the SRG.

The excitation circuit works at low power ratings as it delivers constant operating voltage with pulsating current of rms value does not exceed one ampere. So the excitation circuit can consume its power from the same power supply used for the dc shunt motor.

The control circuit is simply responsible for the energy transformation to and out of the SRG based on the continuous tracking of the rotor position with respect to the excited stator winding. It consists of: shaft encoder with line driver (as the position transducer), line receiver, analogue to digital converter (as the excitation current adjustment), EPROM and XILINX programmable logic arrays chip.

## 3. The Excitation Circuit

The function of the excitation circuit is to supply the initiative current pulses into the proper stator phase winding. These pulses will trigger out the full load output current transferred from the input mechanical power. The SRG used in this work is a four phase machine with 8/6 as stator to rotor poles. Figure 2 shows the excitation circuit connected to the stator phase windings including the conducting switches and diodes.

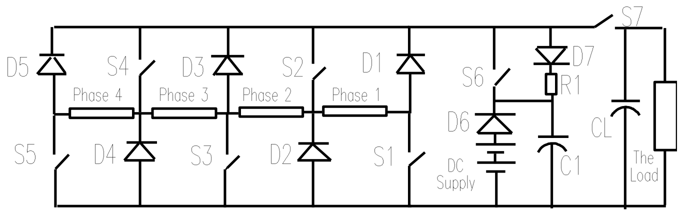


Figure 2. The excitation circuit for the SRG

The switching sequence of the switches shown in figure 2 is performed by the control circuit as it will be discussed later. When switches S1 & S2 are on simultaneously with switch S6, that will pulsate the excitation current from the dc supply into phase 1 through D6. Then when S1, S2 and S6 are off, the current in phase 1 will steadily flow through the diodes D1 & D2 to the load in condition of switching on S7.

For the other phases it is possible to predict the proper devices which should be conducting in both cases of excitation and loading. Table 1 shows the devices which should be in on state for each phase when it is either excited or loaded.

The switching topology used for the SRG in this work minimises the whole needed switches number for the power converter compared with conventional double switch per phase converters[3]. The switches used in this work are IGBT with their predesigned gate drive circuits[4].

## 4. The Control Circuit

The main components of the control circuit used to operate the SRG are: the position transducer, the excitation adjustment commander and the control processor. These parts are described as follows:

| Phase No | Excited | Loaded |
|---|---|---|
| 1 | S6,S1,S2,D6 | S7,D1,D2 |
| 2 | S6,S2,S3,D6 | S7,D2,D3 |
| 3 | S6,S3,S4,D6 | S7,D3,D4 |
| 4 | S6,S4,S5,D6 | S7,D4,D5 |

Table 1. Excitation and loading devices for SRG

### 4.1. The Position Transducer

As the SRG works at considerable high speeds with multiple switching per one revolution, the periphery angle error resolution should be minimised. Shaft encoder is found to be the most suitable position transducer for this objective. The chosen shaft encoder is inherently connected to a line driver which produces double train of pulses A & B each of 1800 pulse per revolution. Actually B is delayed half pulse duration than A. It also produces a clock pulse Z each revolution. A, B and Z signals are filtered and reshaped by the line receiver. The line receiver used in this work is one of the 26LS32 family. The output signals A, B and Z are then inputted to the control processor through the input pins of the XILINX programmable logic arrays chip.

### 4.2. The Excitation Adjustment Commander

The excitation adjustment commander is that component which is responsible for adjusting the excitation level of the SRG. In terms of the SRG operation strategy the excitation level is meant to be the duration angle through which the excitation devices are in on state. There are two ways used to adjust the excitation level. The first one is to use a calibrated analogue signal as the desired input signal, then it is converted to digital signal through ADC to be inputted to the control processor. The second way is to input the desired digital input signal to the control processor directly through deep switches connected between +5 V & the digital ground.

### 4.3. The Control Processor

The control processor is actually the real executor of the whole predesigned operation conditions of the SRG. It consists of the XILINX programmable logic arrays and the EPROM chips. The XILINX chip used in this work is of the X4000 family[5] and it is capable of performing all of the logic processes needed to operate the power converter through its gate drive circuit. It has been designed to contain a counter, a decoder, a data selector and a latch.

A and Z pulses, coming from the line receiver, initiate the counter. Then the decoder pre-sets the counter at the corresponding rotor position angle which indicates till the end of operation for the selected stator phase winding. Not only the EPROM contains all the necessary data to operate the power converter in the different desired conditions, but it also contains the software needed to operate the XILINX chip. The software is transferred directly from the EPROM to the XILINX chip once the control circuit is biased.

The data selector inside the XILINX chip starts its operation based on the B signal arrival coming from the line receiver. As B is delayed half cycle duration than A, that gives the XILINX data selector the ability to avoid any disturbances might appear at operation starting. As the default input commander selects the desired excitation level, the data selector responds to that selection and moves the corresponding data from the EPROM to the XILINX chip. The data selector outputs the data to the gate drive circuits through a latch enabled by the B signal. Finally the gate drive circuits fire the determined power converter switches in conjunction with the excited or loaded stator phase winding.

In case of variable speed drives as wind turbines, a frequency to voltage transducer can be used to transfer the shaft encoder signals A and Z to a corresponding analogue TTL DC voltage level. This analogue signal is to be the input of the ADC. Figure 3 shows the details of the XILINX chip structure.

## 5. The Predicted Results

The output current pattern can be derived based on the equivalent circuit representing the specific mode of operation. The different modes of operation can be categorised as: excitation mode, positive $dL/d\theta$ loading mode and negative $dL/d\theta$ loading mode.

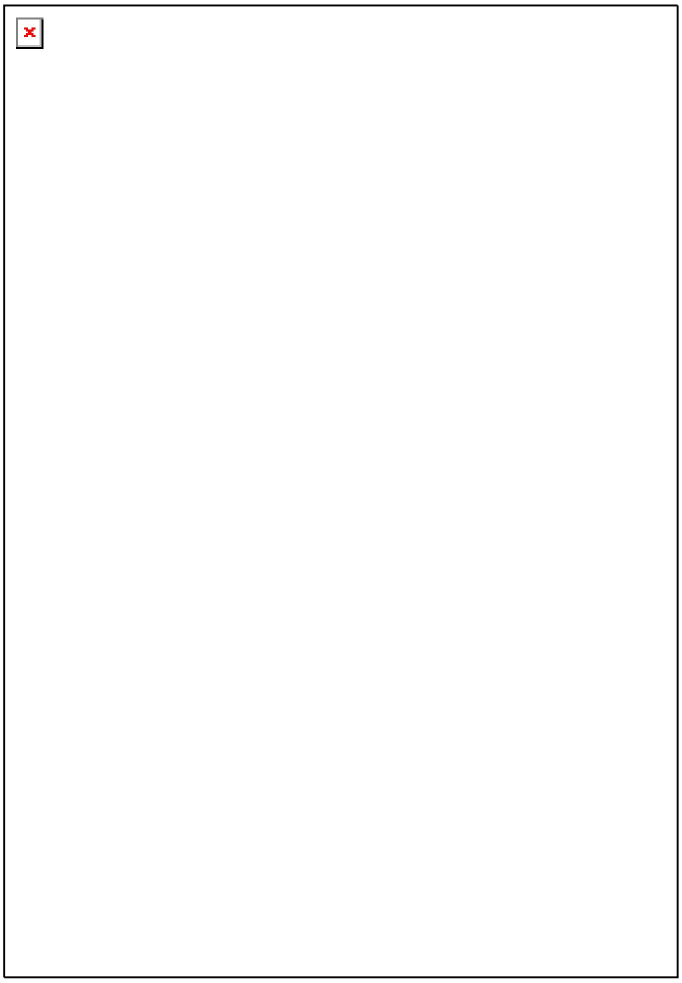

Figure 3. The XILINX chip equivalent circuit

In the excitation mode, the closed loop voltage equation is:

$$V = i(t) \cdot R + i(t) \cdot \omega \cdot (dL/d\theta) + L \cdot di(t)/dt \quad (1)$$

where:
$i(t)$ = the instantaneous current value,
$t$ = time,
$V$ = the applied excitation voltage,
$R$ = the excited stator phase winding resistance,
$\omega$ = the periphery angular velocity,
$L$ = instantaneous excited phase inductance,
$\theta$ = instantaneous rotor position angle with respect to the excited stator winding.

L and θ can be expressed as:

$$L = L_o + (dL/d\theta) . \theta \qquad (2)$$

$$\theta = \omega . t \qquad (3)$$

where $L_o$ is the minimum inductance value. Solving to get the current i(t) results in:

$$i(t) = V/(K+R) \ [\ 1 - e^{-(K+R)\ t\ /\ L}\ ] \qquad (4)$$

where:

$$K = \omega . (dL/d\theta) \qquad (5)$$

In the positive dL/dθ mode, the closed loop voltage equation is:

$$i(t).\omega.(dL/d\theta) = i(t) . [\ R + R_l\ ] + L . di(t)/dt \qquad (6)$$

where $R_1$ is the load resistance.

Solving to get the current i(t) in this mode, then:

$$i(t) = I_1 . e^{+(K - R - R_l)\ t\ /\ L} \qquad (7)$$

where:

$$I_1 = K_d\ V/(K+R) \ [\ 1 - e^{-(K+R)\ \theta_1\ /\ \omega L}\ ] \qquad (8)$$

and $\theta_1$ is the excitation angle duration, while $K_d$ is a factor depends on the voltage dropped while switching the power converter.

In the negative dL/dθ mode, the instantaneous excited phase inductance turns to be:

$$L = L_m - (dL/d\theta) . \theta \qquad (9)$$

where $L_m$ is the maximum inductance value. The instantaneous current value will now be in the form:

$$i(t) = I_2 . e^{-(K + R + R_l)\ t\ /\ L} \qquad (10)$$

where

$$I_2 = I_1 . e^{+(K - R - R_l)\ \theta_2\ /\ \omega L} \qquad (11)$$

and $\theta_2$ is the excitation angle duration started from stator phase loading and ended with maximum inductance value achieving.
during the excitation period, as $S_7$ is turned off, the capacitor filter $C_L$, shown in figure 2, submits the load current. The current trajectory in this interval is almost pulsating as both of $C_L$ and the load acts as the snubber circuit for $S_7$. Also the switch $S_6$ has its own snubber circuit, as the diode $D_7$ and the resistance $R_1$ are used to freewheel the resulted current when $S_6$ is switched off. The diode $D_6$ is put in such a way to prevent the switch off current from interfering with the DC excitation supply.

The load current per phase for one complete cycle operating conditions of 120 V, 1500 rpm is shown in figure 4.

Figure 4. The estimated load phase current at 120 V, 1500 rpm

## 6. The Experimental Results

A test rig for the SRG operation has been installed. It consists of SRG, DC shunt motor and the shaft encoder. All are aligned on a mounted bed. The necessary wiring for connecting the mounted elements with the control circuit, the gate drive circuit and the power converter has been installed with the monitoring equipment. Figure 5 shows both of the SRG excitation and output load currents for only one phase operation.

In order to operate the SRG with its full capacity, the excitation circuit shown in figure 2 has been used. For each operating driving speed and excitation voltage, there is an optimised excitation conduction period. In this stage of SRG operation, deep switches connected directly to the excitation adjustment commander was used to adjust the excitation conduction period. Figure 6 shows the same measured currents for the complete four phase operation of the SRG.

Figure 5. Excitation and load measured currents for one phase of the SRG at 120 V, 1500 rpm.

The excitation & load rms current values, measured at the same operating conditions, are found to be 0.18 & 3.22 amperes respectively. Taking into consideration the primover input power submitted to the SRG, the whole SRG efficiency is found to be 69 % which can be initially accepted.

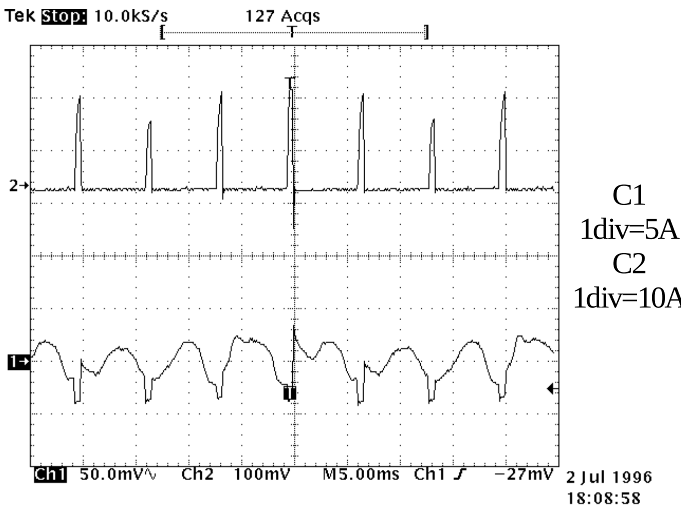


Figure 6. Excitation and load measured currents for the SRG four phase operation 120 V, 1500 rpm.

**Conclusion**

The experimental implementation of the separately excited SRG has been investigated using a laboratory test rig. The excitation of the stator winding has been done separately. The excitation current is governed by the control circuit and can be modified to suit variable speed primovers. The SRG operation can be easily adopted by microcontrollers.

**References**


[1] Lawrenson, P.J., Stephenson, J.M., Blenkisop, P.T., Corda, J., and Foulton, N.N. :,”Variable-speed switched reluctance motors”, IEE Proc. B, Electr. Power Appl., 1980, 127, (4) pp. 253-265.

[2] Abouzeid, M. :”The wind driven photovoltaic excited stand-alone axial field switched reluctance generator”, Al-azhar engineering fourth international conference, December 1995, pp. 374-383.

[3] Pollock, C., and Williams, B. :”Power converter circuits for switched reluctance motors with the minimum number of switches”, IEE Proc. Vol. 137, Pt. B, No. 6, November 1990, pp. 373-384.

[4] Pollock, C. “Power converter circuit for switched reluctance motors”, Ph. D. Thesis, Heriot-Watt University, Edinburgh, UK., 1989.

[5] “The Programmable Gate Array Design Handbook”, Handbook, the Programmable Gate Array Company, 1987.