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Conversion of a Switched Reluctance Motor to Operate as a Generator for Wind Power Applications

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***Abstract*: climate change effect become number one concern in many countries due to the effect that will have on human life. Renewable energy found to be one of the most effective ways to overcome this problem, wind energy is part of the renewable and one of the most growing areas in this field. In this paper the definition of switched reluctance generator and the principal of operation will be discussed, the excitation cycle and its relation to the switching parameters, methods on the switching phenomena will be discussed, low speed circuit and high speed circuit will be explained, output power of the SRM**

I. Key Words

Renewable energy, Switched Reluctance Generator, new generation technology, green house effect

II. Introduction

Switched reluctance generator is a new machine that will convert mechanical power into electrical power; this machine has many advantages when it comes to wind power generation than the permanent magnet and induction generator [1]. The cycle of this machine consist of two stages, excitation and generation stage, the determination of these two stages will determine the efficiency of the machine. The boom in the power electronics market gave the advantages of developing the controller and the switching phenomena for this machine. IGBT or MOSFET transistors will be used as switching device in this controller, for rotor detection can be use a sensor like the Hall Effect for example or a sensor less circuit that rely on reading the inductance value in the winding to determine the rotor position. This paper will discuss the using of the Hall Effect sensor to determine the rotor position and the switching angle, two proposed method one is for high speed and one for low speed will be discussed in this paper and that will depend on the excitation voltage.

In this paper the following has been used during the experiment:

- 1 hp switched reluctance machine 8/6 rated current at 5 amps
- BUZ71 MOSFET power transistors
- IGBT
- 55100 Mini Flange Mount Hall Effect Sensor
- Permanent magnet
- Bipolar BC107
- 74HC/HCT74 Dual D-type flip-flop
- AD8564 Quad 7 ns single supply comparator
- DC power supply for the excitation
- AC 50 hz power supply for the inductance test of the winding

III. Coil Inductance

Equation (1) shows the non-linear inductance model for SRG after taken into consideration the symmetrical of the inductance about the y-axis in the section between $[-\pi/P_r, \pi/P_r]$. This Fourier series of inductance is a function of the excitation current and the rotor angle $L(\theta, i)$. The value of the inductance is constant and periodic with period equal to 2 /P_r where, Pr is the number of rotor poles:

$$L(\theta,i) = L_0(i) + \sum_{n=1}^{\infty} L_n(i)\cos(n\,\mathrm{Pr}\,\theta) \qquad (1)$$

The result of the first 4 harmonics is shown in equation (2) will be acceptable as a final result of the inductance calculation; therefore:

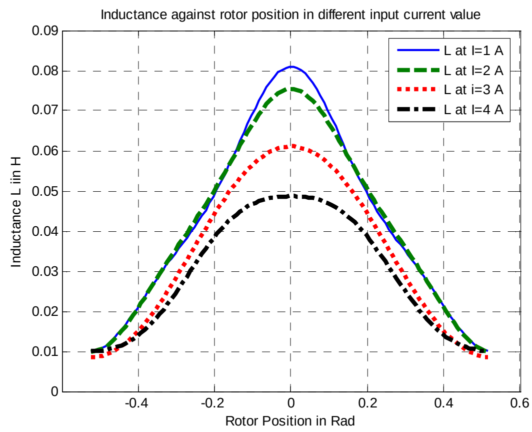

Figure (1) inductance vs rotor positions

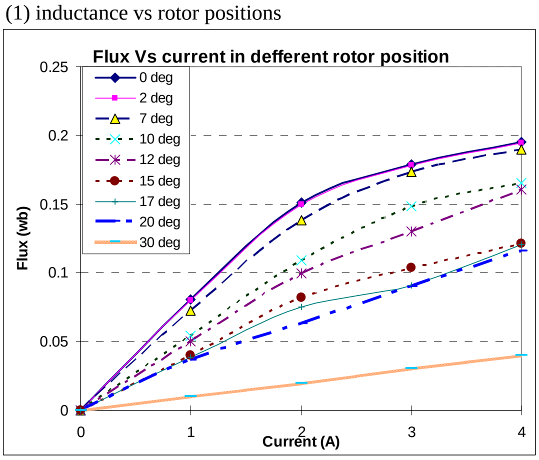

Figure (2) Flux vs current in different at different current and rotor position

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$$L(\theta,i) = L_0(i) + L_1(i)\cos(\Pr\theta) + L_2(i)\cos(2\Pr\theta) + L_3(i)\cos(3\Pr\theta) \quad (2)$$

Figure (1) and (2) shows the experimental result of the inductance of the machine as well as the flux, the results shows the inductance in respect of the rotor angle and the excitation current.

IV. SWITCHING PHENOMENA

The determination of the switching will determine the excitation and the generation mode of the machine, in this section some discussion in regard to several proposed idea of the switching will be shown.

First proposal is under the following conditions:

- The excitation voltage is 30 volts with limited current of 5 Amps
- The speed of the machine wont exceed the 150 rmp
- The total resistance of the winding is 6.5 ohms
- Figure 3 and 4 show the sensing arrangement

Under these conditions the coil will be fully excited under the 4 amps excitation current, the coil is fully excited in $5\times\tau$ and τ is the time constant and equal to $\frac{L}{r_{phase}}$.

Figure 5 shows the inductance in respect to the rotor position; it shows where the excitation and generation stages are. Figure 3&4 shows the Hall Effect components placement on the rotor and stator, the output of the Hall Effect will was fed to the D flip flop and the output of the flip flop was fed to the switching bipolar BC107 transistor.

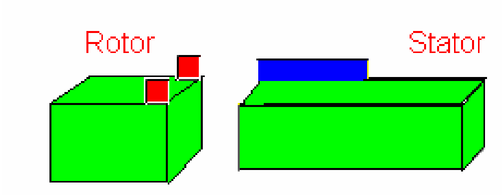


Figure (3) Hall Effect position

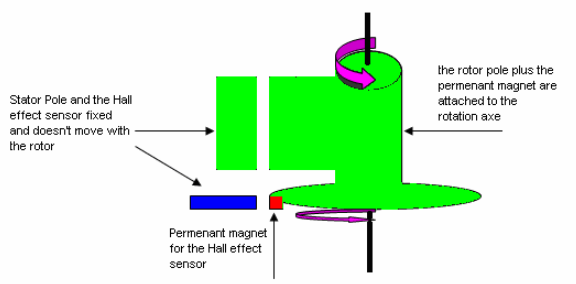


Figure (4) arrangement of the Hall Effect components on the SRG

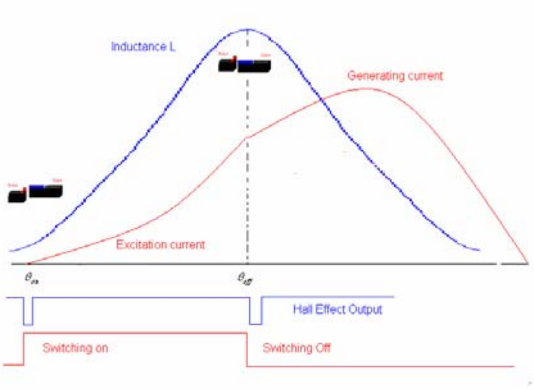
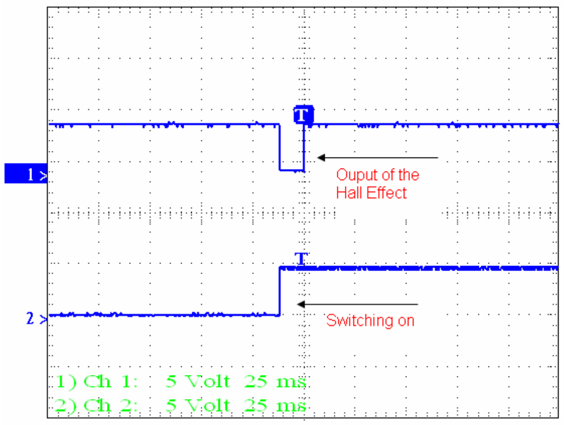
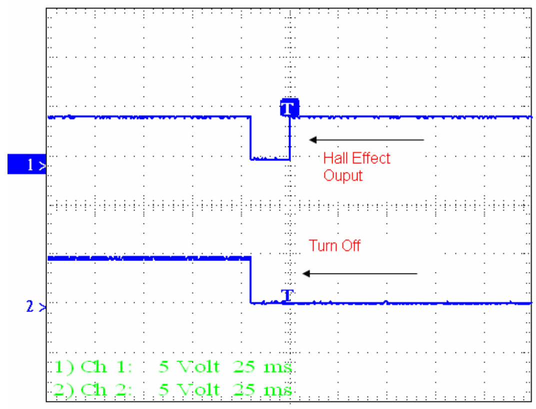


Figure (5) the on and off using the Hall Effect circuit



(a)



(b)

Figure (6) the experimental output of the Hall Effect and the switching on and off of the transistor

Figure 6 shows the experimental switching in respect of the hall effect output, when the first permanent magnet cross the Hall Effect the output of the Flip Flop will be active high and the switching transistor is on, when the second magnet cross the hall effect the output of the Flip flop turn low and the transistor switched off, the position of the magnet and the Hall Effect determine the On and Off stage. Measuring the current that run through the winding of the stator under this condition is 4 amps. This circuit only will be efficient under low speed; high speed doesn't allow the magnetic field to be built to meet the generation mode, there fore other arrangements is needed.

Second proposal is under the following condition:

- Speed higher than 200 rpm
- Excitation current higher than 5 amps,

- The total resistance of the winding is 1.5 ohms

At higher speed than 150 rpm, the first proposal won't be efficient as the excitation in the winding wont reach the required level, to over come this problem a higher excitation current is required, a new circuit to overcome any possible damage to the winding is needed, two proposed method one is the hard current chopping and the second is soft current chopping

The proposed tested circuit is shown in figure 7, is shows the Hall Effect sensor output and the output of the current sensor circuit. The output of the flip flop will be the activating signal of the switching transistors. Figure (8) shows the proposed output waveform, the switch on will depend on the Hall Effect output and the switching off will depend on the current sensing circuit output.

The back emf exist in the shaded area in figure (9), the excitation current increases at higher ration in this area due to the existence of back emf, that will have some small impact on the speed of the rotor but will be neglected at high speed.

The switching on for the tw proposed method can be adjusted by placing the permanent magnet at different location. The off position can be changed for the first one by relocating the permanent magnet on the rotor location at different place and for the second one by variant the reference current.
The first one show that have better output under the hight speed and can achieve the highest excitation stage by choosing the right place for the magnet; The second one will have a better performance under high speed,

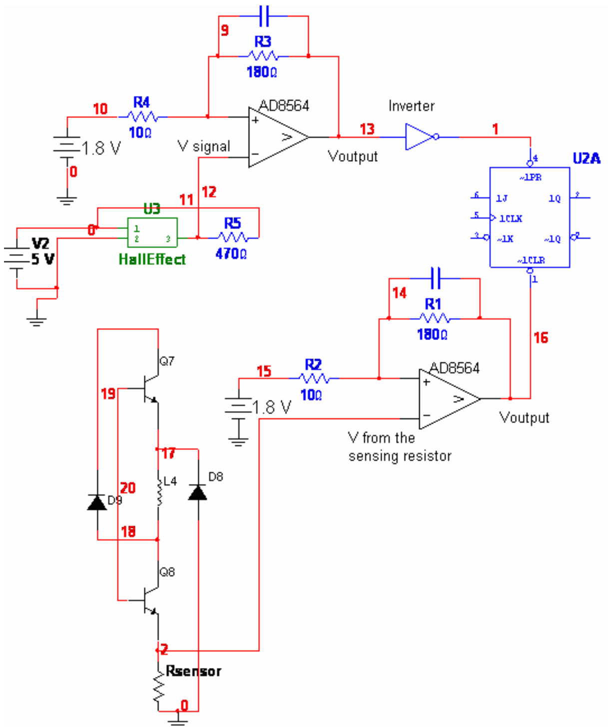


Figure (7) proposed tested circuit

The output of the second proposed switching shows a higher efficiency. The reason is the higher speed and it is ability to use the maximum excitation current which leads to higher magnetic field. This will give the machine to operate at higher efficiency. During the experiment it is found that the excitation energy is higher than the generating energy, that will lead to lower efficiency, this excitation energy will depend on the winding characteristics and the cross section area of the stator and rotor. Refer to the formula $L = \frac{\mu N^2 A}{l}$ where L is the inductance in the coil, N is number of turns, A is the cross section area, l is the length of the cupper and μ is the permeability of the cupper. By increasing the number of turn in the coil the inductance will increase. A modification on the winding of the switched reluctance motor machine done, figure 9 shows the new flux density curve for the modified machine. Figure 10 shows the energy level between the old machine and the modified one, it is clear that at lower current the modified machine have the ability to produce higher power output at the same speed.

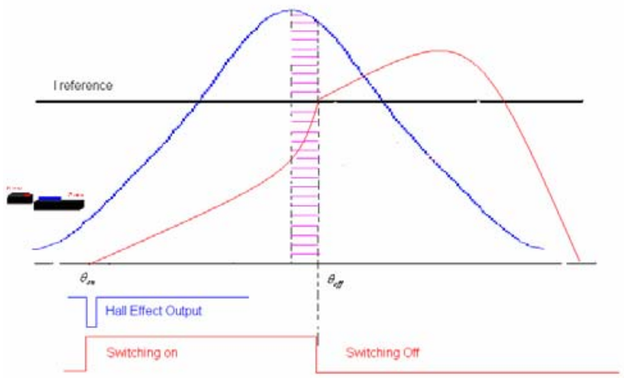


Figure (8) the output voltage of the circuit in figure (7)

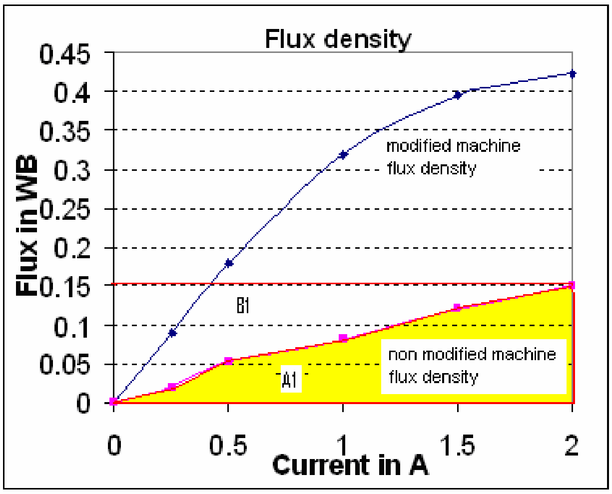


Figure (9): flux density at different stator winding N

From figure 9 and 10 it is possible to calculate the ratio between the generation energy and the excitation energy using the following:

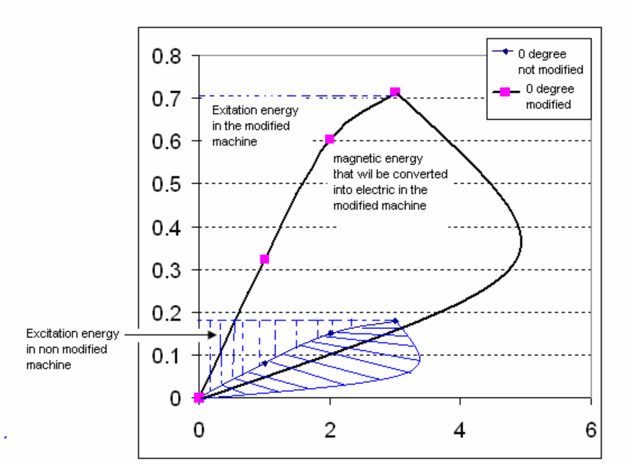


Figure (10): energy conversion graph under different stator windings numbers

Area B1+A1=2*0.15=0.3

Area A1=0.115 using the integration

$$A_1 = \int_0^{0.2} L(0,0.2)\times idi + \int_{0.2}^{0.4} L(0,0.4)\times idi + \int_{0.4}^{0.6} L(0,0.4)\times idi + \int_{0.6}^{0.8} L(0,0.6)\times idi + \int_{0.8}^{1} L(0,0.8)\times idi$$
$$+ \int_{1}^{1.2} L(0,1)\times idi + \int_{1.2}^{1.4} L(0,1.2)\times idi + \int_{1.4}^{1.6} L(0,1.4)\times idi + \int_{1.6}^{1.8} L(0,1.6)\times idi + \int_{1.8}^{2} L(0,1.8)\times idi \quad (6)$$

A1=0.115, there fore B1=0.185 which mean this machine can act as motor under better performance when acting as generator.

Similar works will be carried out for to the modified machine flux. The results are as shown

A=0.5, B=0.35 where A is the energy during generation and B is the excitation energy.

The ration between A1/B1 is less than one

The ration between A/B is bigger than one

Using the proposed testing circuit in figure 7 and by using a load of 50 Ohms across the winding of the generator, the machine has been tested under the both conditions.

Figure 10 shows the experimental output result, it is clear that the output under the second proposed machine is much higher and more efficient.

The experimental result shows that if the ration between the stored energy and excitation energy is higher than one the output of the machine is higher and more efficient when operating under generating mode.

$$A_1 = \int_0^2 \varphi di \quad (3)$$

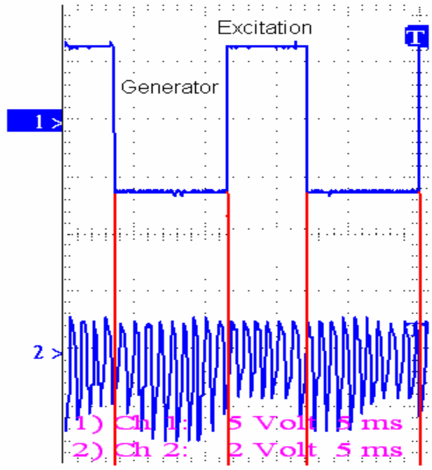
Replacing the flux with it is value

$$A_1 = \int_0^2 L(\theta, i)\times idi \quad (4)$$

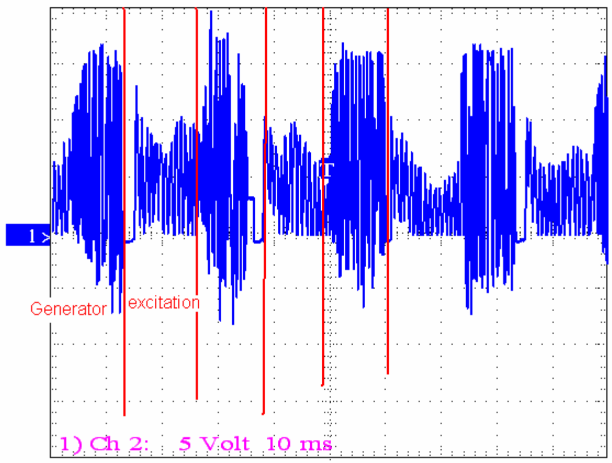
Using the aligned stage for the calculation that mean θ=0

$$A_1 = \int_0^2 L(0, i)\times idi \quad (5)$$

To solve this integral, an experiment result has been conducted for the current interval [0, 2] A using 0.2 amperes step.



(a)



(b)

Figure (10); a, tested result for the first method; b, tested result for the second method

V. CONCLUSION

A switched reluctance motor can act as generator by changing the firing angle in the controller, to obtain higher efficiency of the machine it is recommended to change the winding of the stator to maximise the generation energy and minimize the motoring energy. Using a hall effect to determine the on an off mode, have limitation and its efficiency is very low when used in small scaled generator, it will perform better at high power machine where the number of winding is high and the cross section area is bigger. The second proposed methods where the current sensor will determine the off mode, have better performance when it comes to small generator. This study shows that in order to have an effective performance from a switched reluctance motor when operating as generator, the following steps are vital:

- Re-arrange the winding
- Change the firing angle
- Proper excitation source

VI. REFERENCE

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