Analysis and performance of a Switched Reluctance Generator for wind energy conversion

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Abstract: The concept of operation for the switched reluctance generator is divided into two sections, first is the excitation stage and second is the generating stage. This paper discuss the determination of the coil excitation in the SRG, the switching phenomena, requirement to protect the machine from electrical damage as well as the electric losses limitations.

I. INCTRODUCTION

Climate change is one of the focus issues that leaders world wide are discussing and trying to find an acceptable solution before it is too late. The technology is one of the major areas that have been focus on to deal with these issues. The scientist world wide are trying to find a better and more effective way to use the nature energy or to minimise the carbon dioxide from feeding into the environment, as well as increasing the efficiency of the electric machine. Renewable energy became an important topic when it comes to deal with climate changes, renewable energy in all faces, solar system, hydro system, wind energy, co-generation are the aim for improvements in many country due to its impact on the climate changes. Wind energy is one of the nature ongoing sources that help the life cycle of the planet to continue, wind energy is not a simple breeze that can push a tree it could be strong to take buildings off, it is one of the modern energy sources to generate electricity. Using an ongoing source to produce electric power for the human daily need, will give a more stability and cheap way to maintain the human demand under control, no need to worry about the coal or fuel reserve, as soon the wind stop from the planet the life will end.

The IPCC (the intergovernmental panel on climate change) sent an important warning to the word nations for the need of use a low-carbon to avoid the dangerous complications to the climate changes and the danger on the society. Due to many factors wind energy became a main renewable source to convert nature energy into electric power for daily use. The consumption of the electric energy increases on a high rate in the past decade, this increase forces the international society to find more efficient way to overcome the climate change that caused by this increase. The majority of the high capacity wind generator used are induction generator, this machine have few disadvantages such as winding losses and low efficiency, a new machined called switched reluctance generator started to develop to be used as wind generator, this machine has few advantages over the AC conventional machine [1]. The boom in the technology market helped in securing a high efficiency output for the switched reluctance generator and made it easier to build more effective controller.

The main advantages that the switched reluctance generator has over the conventional AC machine that will be highlighted in this paper are:

1. higher efficiency
2. eliminate to electric losses in the rotor
3. fast response
4. cheap manufacturing cost

These four points made the international research take a deeper look in using the SRG as possible sources for the wind energy conversion. SRG is a simple machine that consisted of a winding around the stator poles and of a silent rotor poles, this gives the SRG the fast response under the change of load condition due to lighter rotor. The elimination of the rotor winding in the induction generator made the SRG cheaper to manufacturing also did eliminate the electric losses in the winding. The higher the efficiency the lower the cost per KWH for the wind energy

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

II. PRINCIPAL OF OPERATION

The basic operation of the machine can be divided into tow sections, first the operation as a motor (SR motor) and the second is to operate as generator (SRG), in this paper the concern is in the machine when operation under as a generator, the operation cycle will be divided into two stages, first is called excitations and the second is generation stage, the on and off mode between these two stages called the firing angles for the machine. During one cycle, the machine will be excite, using external sources which could be a capacitor or a battery, the magnetic field that created by the excitation will be converted into electric power during the second stage of the cycle using the wind energy as a mechanical source. The firing angel will depend on the characteristics of the machine (inductance, flux density, rated values), the inductance of the machine will determine the output of the machine, when operation the machine as generator, the flux density for the motoring stage must be minimum to avoid losses and when operation as motor the generating stage should be at its lowest value, this will be explained in more details in this paper.

Inductance

As mentioned earlier, depend on the inductance characteristics will determine the type of the machine and the characteristics of the output power. The analysis of the inductance will be on the non-linear inductance model which is based on the Fourier series of inductance; the 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 $2\pi/P_r$ where, P_r is the number of rotor poles. By applying Fourier series and taken into consideration the symmetrical of the inductance about the y-axis in the section between $\left[-\pi/P_r,\pi/P_r\right]$, the following equations represent the relation between the inductance, the current and the rotor angle:

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

The result of the first 4 harmonics will be acceptable as a final result of the inductance calculation; therefore:

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

it is clear that the inductance of the SRG depend on the rotor position as well as the excitation current. Recall the requirement of the coil excitation and the current behaviour in the coil as stated in the equation below.

$$i_{increase}=\frac{v}{R}\left(1-\exp^{-t\frac{R}{L}}\right) \qquad (3)$$

$$i_{decrease}=\frac{v}{R}\left(\exp^{-t\frac{R}{L}}\right) \qquad (4)$$

$$\tau=\frac{L}{R} \qquad (5)$$

Where $i_{increase}$ represent the current feeding into the coil, $i_{decrease}$ represent the current leaving the coil and τ is the time constant.

Figure 1 shows the current behaviour inside the coil and it is nominated time constant.

According to the science the coil will be fully excited at 5τ. This is a vital when it comes to determine the length of the excitation stage, the determination of the on and off of the firing angle will be determined to allow maximum excitation in the winding of the stator. The time constant will determine the excitation of the coil. In the SRG case the inductance of the coil is a function of the rotor position, using Matlab figure 2 shows the time constant in respect to the rotor position of the machine

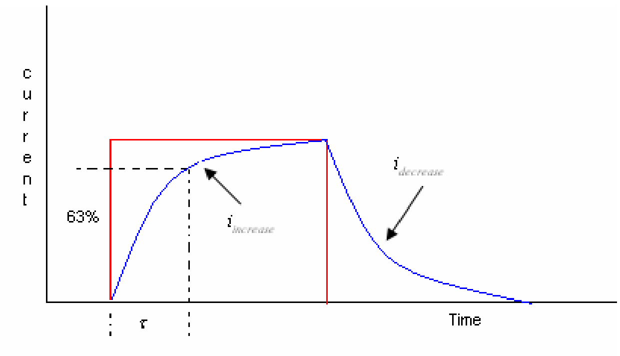

Figure (1) current behaviour inside a winding coil

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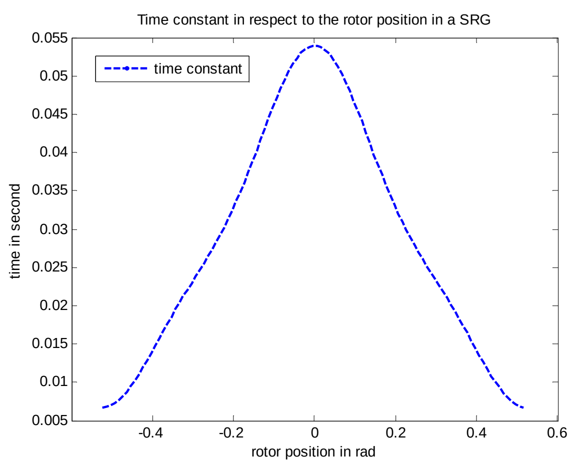

Figure (2) time constant in respect to the rotor position

Figure below shows the proposed excitation switching method:

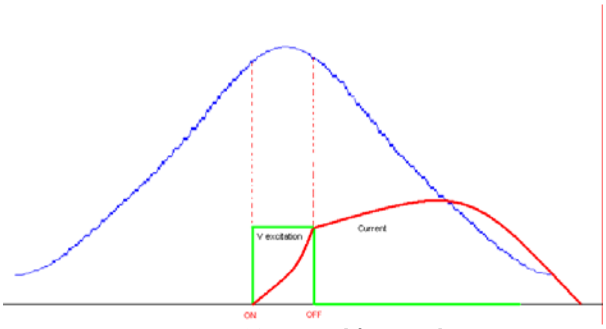

Figure (3) proposed firing angle

Figure 2&3 shows that the time constant of the nominated coil will be around 55 ms that mean the excitation time will have to reach the 200 ms in order for the machine to reach the maximum excitation. That mean this machine must operate at low speed and that will impact on the output power as shown in the below equation:

$$P(\theta, i_j) = \left[\frac{1}{2}\sum_{j=1}^{n}\frac{dL_j(\theta)}{d\theta}i_j^2\right]w \qquad (6)$$

Where w is the rotor speed in rad per second

The current increase of a ration of V/L therefore in order to reduce the time constant it is important to either increase the excitation voltage or decrease the inductance. Increasing the voltage will increase the current and leave the winding exposed to the electric damage, to overcome this problem 2 method can be proposed, one is to increase the resistance and one to set a sensing circuit.

The maximum current are represented in equation 7, to maintain the maximum current as required, an extra resistance will be attached in series with the winding of the stator.

$$I_{Max} = \frac{V}{R} = \frac{2V}{2R} = \frac{3V}{3R} \qquad (7)$$

The maximum current I_{Max} is fixed to its required value and preventing any damage from occurring in the coil. The time constant will be shows in equation 8, it is clear how the time constant is decreasing by using a higher voltage source with an extra resistance in series..

$$\begin{cases} \tau_1 = \dfrac{L}{R} \\ \tau_2 = \dfrac{L}{2R} \\ \tau_3 = \dfrac{L}{3R} \end{cases} \qquad (8)$$

This method leads to high electric losses in the extra resistance. Figure 4 shows the current behaviour inside the coil under different voltage and time constant, it is clear that this method will lead to a shorter time constant which lead to a higher operational speed. One time constant represent around 63% of the maximum current.

As stated before the slop of the current waveform is proportional to V/L figure 5 shows the current behaviour by increasing the voltage. Also the proposed cut off to maintain the maximum current to prevent any damage to the coil.

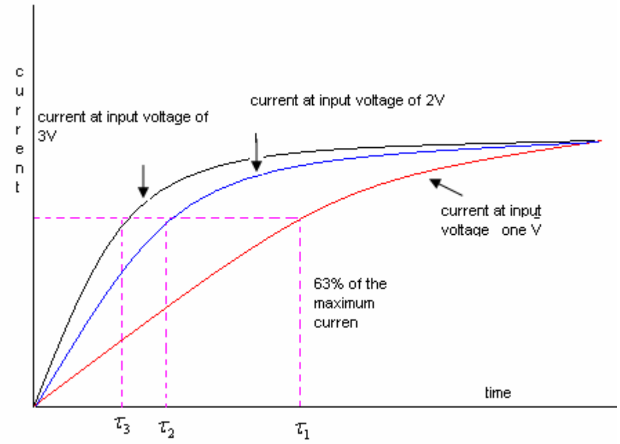

Figure (4) current in the coil under different time constant

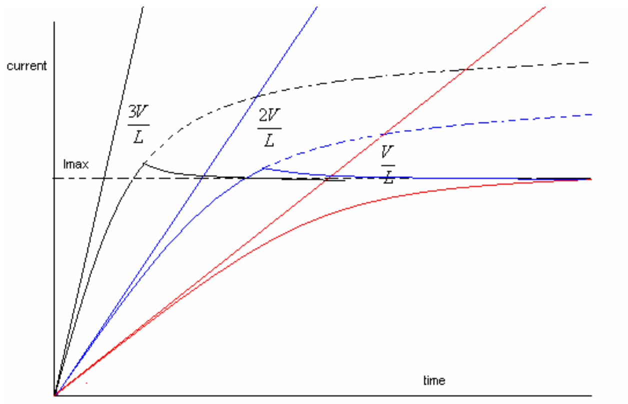

Figure (5) shows the proposed Imax

III. The Controller

The controller is the circuit that determine the firing angles for the machine, the typical controller consist of two switching transistors and two diodes for a single phase, figure 6 shows a typical 4 phase controller. figure 7 shows a single phase switching phenomena, when the switches S_1 and S_2 is closed the machine is under the excitation stage, when the two switched are open the machine is under the generating stage. The voltage will depend on the winding characteristics and can be presented in equation 4

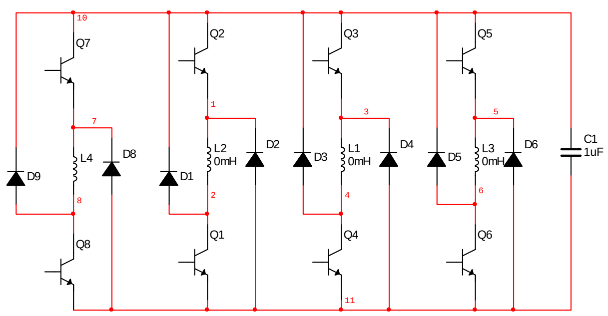

Figure (6) 4 phase’s controller

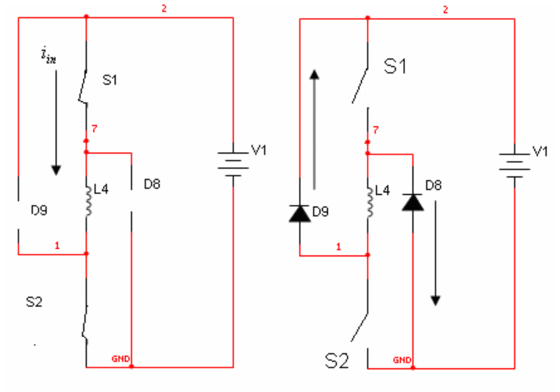

Figure (7) single phase controller under excitation and generation

$$\begin{cases} S_1 \,\&\, S_2 closed, i_{ph} = i_{excitation} \,\&\, v_{ph} = v_{excitation} \\ S_1 \,\&\, S_2 open, i_{ph} = i_{generator} \,\&\, v_{ph} = v_{generator} \text{..........(9)} \\ v_{excitation} = Ri + L\dfrac{d(i)}{dt} \,\&\, v_{generator} = Ri + w_m i \dfrac{d(L)}{d\theta} \end{cases}$$

The proposed switching for the controller is shown in figure 8 it is clear that the switching will take the alignment stage during the excitation stage.

Figure 8 shows the energy conversion graph in the SRG, area A represent the excitation/motoring energy when the machine are used as generator/motor and B represent the energy that will be converted into electric power when the machine is used as generator

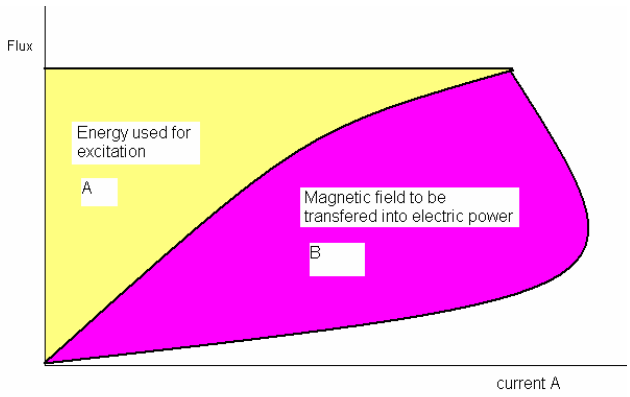

Figure (8) energy conversion in the SR Machine

The ration between the generating energy and the excitation energy will determine if the machine will be more suitable to operate as a motor or generator.

$\dfrac{B}{A} \leq 1$ the machine can perform better under the motoring stage and if $\dfrac{B}{A} \geq 1$ the machine perform better under the generating stage. The higher the ration the better for the machine to operate as a generator.

IV. Experiment

The experiment started by measuring the inductance and the flux density of the machine. The output results are shown in the figure 9 and 10.

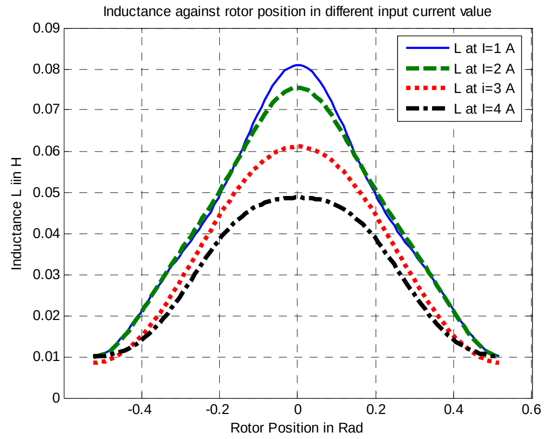

Figure (9) inductance vs rotor positions

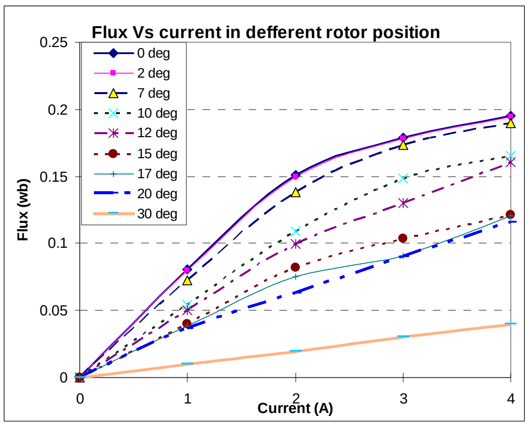

Figure (10) Flux vs current in different rotor at different current position

The following steps are undertaken to determine the energy ration for this machine

The area $B = \int_0^2 \varphi di$

Replacing the flux with it is value

$B = \int_0^2 L(\theta, i) \times idi$ Using the aligned stage for the calculation that mean θ=0

$B = \int_0^2 L(0, i) \times idi$ To solve this integral, an experiment result has been conducted for the current interval [0, 2] A using 0.2 amperes step. To determine the inductance value for each 0.2 amperes step.

$$B=\int_{0}^{0.2}L(0,0.2)\times idi+\int_{0.2}^{0.4}L(0,0.4)\times idi+\int_{0.4}^{0.6}L(0,0.4)\times idi+\int_{0.6}^{0.8}L(0,0.6)\times idi+\int_{0.8}^{1}L(0,0.8)\times idi$$

$$+\int_{1}^{1.2}L(0,1)\times idi+\int_{1.2}^{1.4}L(0,1.2)\times idi+\int_{1.4}^{1.6}L(0,1.4)\times idi+\int_{1.6}^{1.8}L(0,1.6)\times idi+\int_{1.8}^{2}L(0,1.8)\times idi$$

The ration equal to 1.608 which is higher than one Therefore the machine can operate as generator in a more efficient way than operating as motor.

Second part of the experiment was conducted on the firing angle, set the motor that will be driving the generator on a constant speed and test the switching phenomena. Figure 11 shows the experimental set-up.

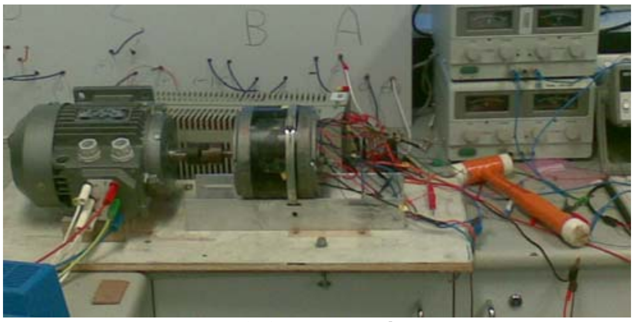

Figure (11) experimental set-up

Figure 12 shows the experimental result when the machine excited with a voltage value of one V under a low speed to allow the maximum excitation for the nominated machine. Under this condition the excitation of the machine is acceptable but due to the low speed the machine operate at low efficiency

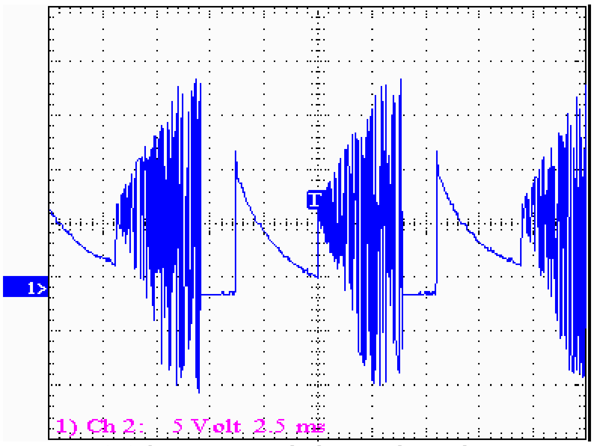

Figure (12) the excitation under low speed normal situation

Figure 13 shows the excitation waveform for the SRG using a higher voltage excitation source at low speed. Comparing the output in figure 12 and 13, the second output is slightly higher but the output of the machine still at low efficiency.

Figure 14 shows the excitation waveform of the SRG under high speed and an excitation voltage value one V, the coil didn't excite due to the high speed, the duration of the excitation is less then on tenth of the time constant, under this condition the output of the machine is almost zero.

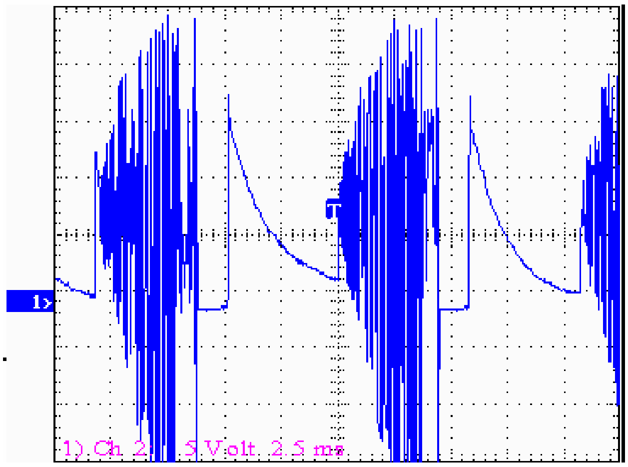

Figure (13) excitation waveform under higher excitation voltage

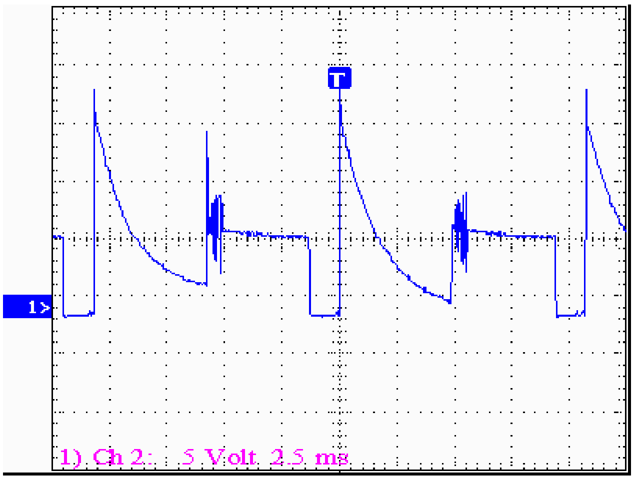

Figure (14) excitation under high speed switching for normal excitation voltage

Figure 15 shows the excitation wave form under high speed and an excitation voltage value more than 3V, it is clear that the excitation output is higher than the one in figure 14. The output power of this excitation is higher than the one in figure 11 or 12.

Figure 16 shows the tested circuit, the Hall Effect device is to determine the rotor position as well as to determine the turn on of the switching transistor using the PRE of a J-K flip flop. The sensing resistor is to maintain the current to its nominated value in the stator winding by switching the transistor off using the CLR of the J-K flip flop.

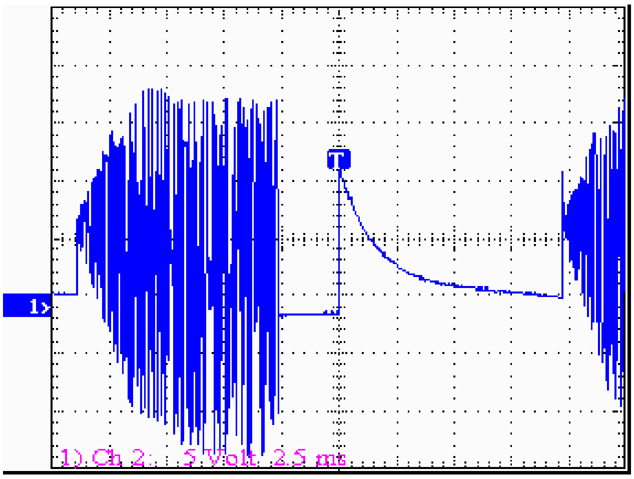

Figure (15) excitation under higher voltage source using a chopping circuit

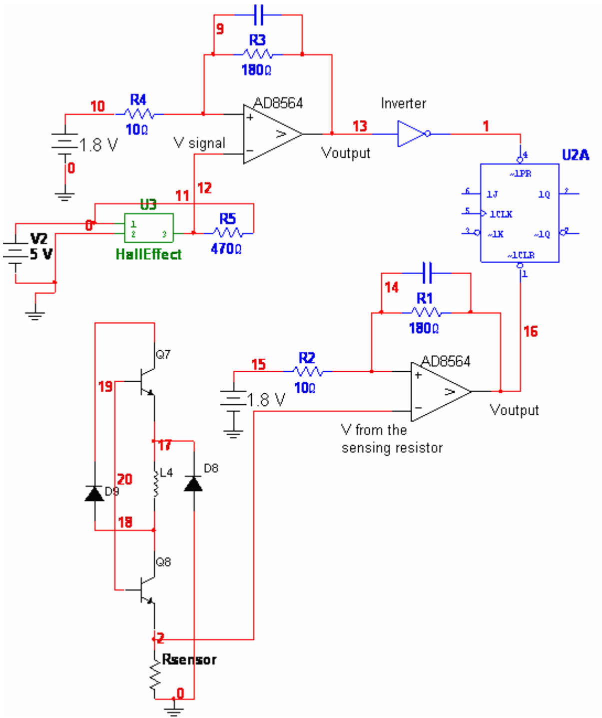

Figure (16) tested circuit

V. CONCLUSION

The output of this paper shows that by using or applying a higher excitation current will lead to a higher magnetic field stored in the stator winding which lead to higher output power, also give the ability to operate under higher switching speed. using a higher voltage source it is recommended to use the sensing resistor method with the high excitation current and not the extra resistance method to limit the electric losses and improve the efficiency the system.

VI. REFERENCE

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