A SWITCHED RELUCTANCE GENERATOR CONNECTED TO THE MAIN GRID AND DRIVEN BY A VARIABLE SPEED WIND TURBINE

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ABSTRACT

The paper presents a doubly salient switched reluctance generator for wind energy applications. The generator itself has a simple and rugged construction . It can be designed for low speed applications without suffering from the common problems of conventional generators. Therefore, it can be rigidly coupled to a wind turbine without the need of a gearbox. This system is connected to the main grid and it is not self excited. A non-linear computer model is used to carry out the design procedure. The generator is operated at varying shaft speeds and its torque is regulated so that energy extraction is maximized over the whole variable speed range of the turbine, by controlling both the instant at which each phase winding is excited and the instant at which excitation is removed. Details of generator design parameters and predicted performance are given over the operating range of a Sandia-17-m Darrieus wind turbine. The recommended switching angles for optimum operation with maximum energy capture are given. These optimum combinations of switching angles can be stored in a controller for computerized operation of the system.

Keywords: Switched Reluctance Generator, Wind Energy Conversion, Digital Simulation.

NOMENCLATURE

A	turbine cross-sectional area in m^2;
C_p	coefficient of performance;
D_r	rotor outer diameter;
D_s	:stator outer diameter;
L	:core length;
L_m	:maximum phase inductance, H;
L_o	:minimum phase inductance, H;
n	:turbine rotational speed in rpm;
S_r	:split ratio (D_r/D_s)
T	:coupling torque, Nm;
u	:wind speed in m/s;
V_s	:d.c voltage.
β_r	:rotor pole arc , deg.;
β_s	:stator pole arc , deg.;
ρ	:air density in kg/m^3;
τ_r	:rotor pole pitch, deg.;
ω_m	:mechanical angular velocity of the turbine in radians/s;
θ_{on}	: switch-on angle, deg. (measured from the alignment position of rotor leading edge with stator trailing edge).
θ_c	: conduction angle, deg.;
θ_{cmax}	: fully open conduction angle for two-phase on;
ψ	: flux linkage, Wb.turn;
λ	: Ratio of turbine tip speed to wind speed.

1. INTRODUCTION

Available energy sources are either non-renewable (oil, coal, nuclear, ...) or renewable (solar, wind, tidal, ...). The non-renewable energy sources are running short, cause serious environmental problems and their price fluctuates unpredictably. Of the renewable energy sources both solar and wind energy have received considerable attention. Wind, as a source of energy, has been used for centuries for sailing ships, irrigating land and grinding grain. It is a free and clean energy source, but compared with oil, it is expensive to use in generating electricity due to the high capital costs and the uncertainty of wind. However unexpected upsurge in the fuel prices following the 73-74 oil crisis have led to extensive research activities on the development of efficient and economical electromechanical energy conversion devices for wind generating schemes. With the continuous technical development in the manufacturing of the different components of wind energy systems, wind power may become less expensive and compete economically with other cheap energy sources.

A wind energy system used for generating electricity consists of the following components: turbine (horizontal or vertical), tower, generator, gearbox, various sensors, controls, couplings, brake, transformers, gear switch, protective relays, instrumentation and lightning protection. This system can be connected to the utility grid provided that it produces high quality electricity i.e. constant voltage, constant frequency and low level of harmonics. On the other hand a less expensive wind energy system which produces less quality power can be used to supply electricity for remote areas where the connection with the main electric utility grid is not economical. This is one of the promising applications of wind energy specially in the remote areas of developing countries with good wind regimes, when the country economy is not capable to connect remote areas with the main utility grid. The generators used for wind energy conversion were normally conventional machines such as synchronous , induction and dc generators [1]. But there are many problems associated with conventional generators driven by wind turbines, such as complex construction, relatively higher cost, regular maintenance; also governors, voltage regulators may be needed for maintaining constant voltage and frequency of synchronous generators [2]. On the other hand capacitor banks may be needed for the self excitation of induction generators [3]. The analysis of initial costs for constructing an electric wind system shows that the initial costs of both generator and gearbox amount to nearly 25% of the total cost of the system [4]. So, eliminating the gearbox and using a cheaper and maintenance-free generator will have a good potential for reducing both initial and operating costs of the wind generator system.

The proposed switched reluctance generator system outlined in this paper, shown in Figure (1), consists of a doubly salient variable reluctance machine, a switching circuit, a position sensor and a controller. This system overcomes most of the problems associated with conventional generators driven by wind turbines [5]. Also, this system has high efficiencies over a wide speed range, its power density is relatively high and its torque-speed characteristic can be tailored to perform optimally at different operating conditions with a simple control method [6].

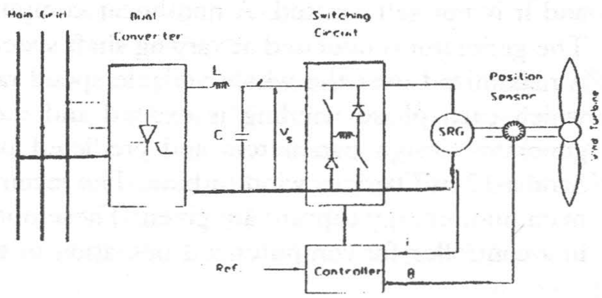

Figure 1. Proposed SR generator wind system.

In this paper the effort is directed toward the development of a cheap, maintenance- free generator which is connected to the main grid via a dual converter and an L-C filter is used to provide a good quality power. It is designed for low speed applications, where it may be directly driven by a Sandia 17-m Darrieus wind turbine operating at variable rotational speeds between 38 rpm and 76 rpm. This generator is of Switched Reluctance type. The principle of operation of Switched Reluctance system in the motoring mode is well documented in the literature [7]. The following section will explain the principle of operation of Switched Reluctance system in the generating mode.

2. BASICS OF SWITCHED RELUCTANCE GENERATING SYSTEMS

The torque of a doubly salient variable reluctance machine is produced from the tendency of the rotor poles to align itself with the excited stator poles. So, a phase winding should be connected to a DC source and a switched circuit is used to switch this excitation sequentially to the proper phase. Therefore, the DC source is needed to produce a magnetic field which forms the energy link between electrical and mechanical systems whether the Switched Reluctance machine is motoring or generating. So, Switched Reluctance Generator can not be self excited as the case for the self excited induction generator when used with a bank of capacitors. When the Switched Reluctance Generator is connected to the main grid it draws its magnetizing current from the supply during the conduction period and its generated energy is returned to the grid during the switch off period. According to the linear theory of energy conversion, the torque equation can be written as :

$$T = \frac{1}{2} i^2 \frac{dL(i,\theta)}{d\theta} \tag{1}$$

This equation shows that torque is independent of current direction (unipolar)as it is proportional to the square of the current.
The inductance variations over one complete cycle are given by the following equations [6]:

$$\frac{dL(i,\theta)}{d\theta} = \frac{L_m(i) - L_o}{\beta_s} = \text{positive for } 0<\theta<\beta_s \tag{2}$$

$$\frac{dL(i,\theta)}{d\theta} = 0 \text{ for } \beta_s < \theta < \beta_r \tag{3}$$

$$\frac{dL(i,\theta)}{d\theta} = \frac{L_m(i) - L_o}{2\beta_s \beta_r} = \text{negative for } \beta_r<\theta<2\beta_s \tag{4}$$

$$\frac{dL(i,\theta)}{d\theta} = 0 \text{ for } 2\beta_s < \theta < \tau_r \tag{5}$$

These equations show that positive torque (motoring) is produced if current exists in the phase winding during the interval of positive inductance variation ($0 < \theta < \beta_s$), while the negative torque (generating) is produced if current exists in the phase winding during the interval of negative inductance variation ($\beta_r < \theta < 2\beta_s$). Therefore, it is essential to have a position sensor that gives signals to the main switches of the proper phase winding to switch them on and off at the correct rotor position.

3. WIND ENERGY EXTRACTION

A wind turbine will extract a fraction of the power available in the wind according to the following equation:

$$P_T = C_p P_w = C_p (1/2 \rho A u^3) \tag{6}$$

Where (C_p) is the coefficient of performance; it is not a constant, but varies with the wind speed, the rotational speed of the turbine and turbine blade parameters (pitch angle and angle of attack). Figure (2) shows the relation between the average value of (C_p) and the ratio of the turbine tip speed to the wind speed (λ), for a Sandia 17-m Darrieus turbine. This figure indicates that (C_p) is very low for a Darrieus turbine operating at tip-speed ratios below about 2. The correspondingly low shaft power is insufficient to overcome friction, so the Darrieus turbine needs a prime mover to get its tip speed up to at least twice the wind speed. As the turbine accelerates it passes through the rated coefficient of performance (C_{pR}) at (λ_R), reaching the maximum coefficient of performance (C_{pm}) at (λ_m). If there is no load on the turbine, it will accelerate until the runaway tip speed (λ_r) is reached. In high winds, the turbine angular velocity may easily exceed design limits at (λ_r); therefore the turbine should not be operated without a load.

The rated rotational speed of the turbine affects its operation and depends on the wind regime of a given site. For certain wind regimes the choice of a rated turbine speed of about twice the mean wind speed could maximize the energy production. But the actual economic optimum may require a smaller rated speed than that which produces maximum energy [3]. For a fixed-speed turbine the maximum coefficient of performance (C_{pm}) is available only at a particular wind speed. A lower coefficient is observed for all other wind speeds, which reduces the energy output. But, for a variable-speed turbine whose speed could be adjusted in relation to the wind speed, a higher average coefficient of performance and a higher average power output could be realized [8].

Figure (3) shows the variation of turbine shaft power output, (P_m) as a function of turbine rotational speed (n) with the wind speed (u) as a parameter of a Sandia 17-m Darrieus turbine. This figure shows that maximum power is reached at 38 rpm in a 6 m/s wind and at 76 rpm in a 12 m/s wind. The curve marked load is drawn to pass through the maximum power at different wind speeds. According to equation (1), this curve is of a cubic form. If the generator coupled to the turbine is capable to accept shaft power according to this load curve and the turbine is free to operate at any speed, then the energy output will be maximized. If this maximum energy output can be obtained without increasing losses or costs, then this wind energy scheme would extract more energy at a lower cost per unit of energy. So, variable speed operation requires a load that has a cubic variation of input power versus rotational speed, or in other words a square variation of input torque versus rotational speed. The torque-speed characteristic of the Switched Reluctance generator can be made to coincide with the load curve shown in Figure (3) by proper choice of the switching angles.

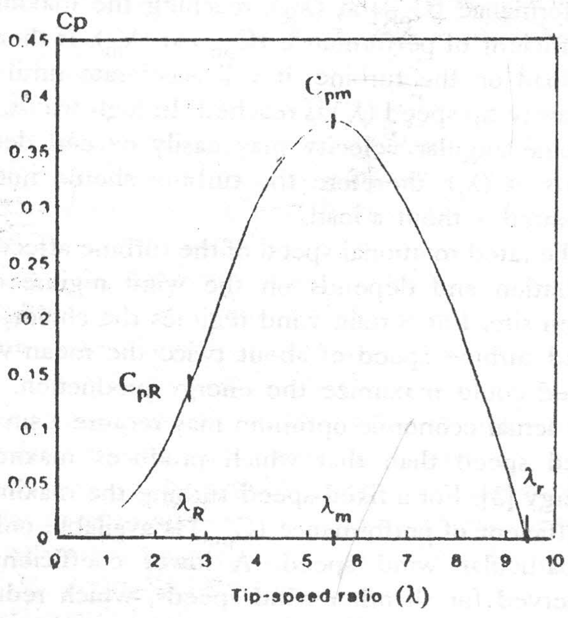

Figure 2. Coefficient of performance versus tip-speed ratio for sandia 17-m darrieus.

4. DESIGN PARAMETERS

In order to design a Switched Reluctance generator, the following data should be specified:

i) Speed range of the prime-mover (turbine).
ii) Required torque-speed characteristic.
iii) Grid line voltage.
iv) The B-H curve of the iron lamination available.
v) Cooling method.

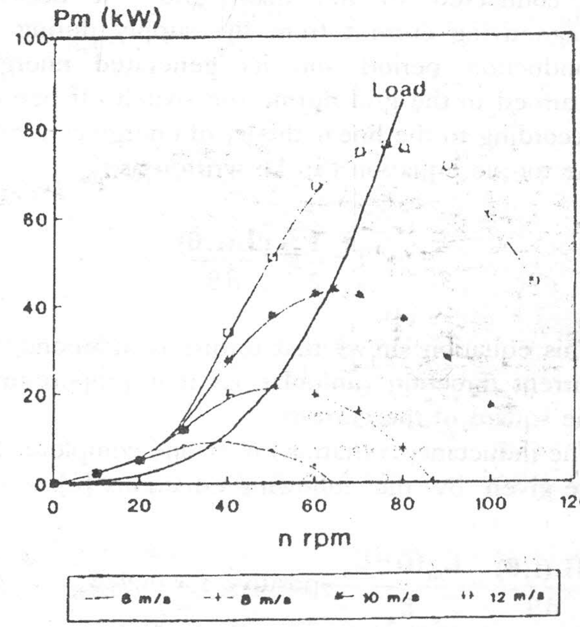

Figure 3. Shaft output power of sandia 17-m darrieus in variable speed operation.

having known the required specification, it is now required to determine the main design parameters of the SR generator. These parameters can be divided into fixed and variable parameters.

(1) The fixed parameters are independent of the prime-mover characteristics and will be chosen from previous experience, past published literature and main grid voltage. These parameters are:

i) Number of phases (m).
ii) Number of stator and rotor poles (N_s and N_r)

iii) Stator and rotor pole arcs (β_s and β_r):
iv) Air-gap length (I_g).
v) Fully open conduction angle (θ_{cmax}) with phase overlapping (two phase on).
vi) Maximum flux density (B_{max}).
vii) Supply voltage (V_s). It depends on the grid line voltage (V_L) and the type of converter circuit used to connect the SR generator to the main grid. For fully controlled dual converter, (V_s) is obtained from:

$$V_s = \frac{3\sqrt{2}V_L}{\pi}\cos(\alpha) \quad 0 \leq \alpha \leq \pi \tag{7}$$

(2) The variable parameters depend on the prime-mover characteristics (maximum output power and maximum operating speed). These parameters are:
i) Rotor diameter (D_r) and core length (L).
ii) Stator outer diameter (D_s).
iii) Shaft diameter (D_{sh}).
iv) Back of core width (C_b).
v) Interpolar air-gap length (g_i).
vi) Number of turns per phase (N).
vii) Wire cross-sectional area (a_w).
viii) End Effect Factor (EEF).

A non-linear computer model [9], has been used to obtain these design parameters for a SR generator directly driven by a Sandia 17-m Darrieus turbine at maximum speed of 76 rpm and having a maximum coupling torque of 9550 N.m, which corresponds to a turbine maximum output power of 76 kW as shown from the turbine characteristic given in Figure (3). The B-H curve of Transil-35 has been used and water cooled system has been considered. This cooling method limits the current density (J_{limit}) of this size of machine to 4 A/mm^2.

The main equations representing this non-linear model are:

$$T = \frac{1}{\tau_\tau}\int \psi(i)\,di \tag{8}$$

$$\frac{di}{dt} = \frac{\pm V - iR - \frac{\partial \psi}{\partial \theta}\frac{d\theta}{dt}}{\partial \psi / \partial_i} \tag{9}$$

These equations are solved numerically using fourth order Runge-Kutta integration method. A simplified flow chart is given in Figure (4) which summarize the design method . convergence of computer program has been assured since the initial and updated parameters are related by the well known proportionality $T \propto D_r^2 L$ Dimensions for both stator and rotor laminations are shown in Figure (5) and the main design parameters are tabulated in Table 1.

Fixed Parameters		Variable Parameters	
Number of phases (m)	4	Stator outer diameter (D_s	0.73 m
Number of stator poles (N_s)	8	Rotor diameter (D_r)	0.42 m
Number of rotor poles (N_r)	6	Core length (L)	1.02 m
Stator pole arc (β_s)	15°	Shaft diameter (D_{sh})	0.1 m
Rotor pole arc (β_r)	15°	Number of turns (N)	352
Air gap length (I_g)	0.0005 m	End effect factor (EEF)	0.2
Fully open conduction angle (θ_{cmax})	30°	Back of core width (C_b)	0.041 m
Maximum Flux density (B_{max})	2 T	Interpolar air-gap length (g_I)	0.133 m
Supply Voltage (V_s)	616 V	Wire cross-section area (a_w)	34.0 mm^2

5. SIMULATED CHARACTERISTICS

The designed parameters of the SR generator were used as input data to the non-linear computer program to predict the generator's characteristics at different turbine rotational speeds.

A quadratic variation of coupling torque versus turbine rotational speed, which match the load curve shown in Figure (3), is obtained by changing both switch on angle and conduction angle. Figure (6) shows the recommended switching angles for optimum operation with maximum energy capture for speeds ranging from 38 rpm to 76 rpm. These optimum combinations of switching angles can be stored in the controller for computerized operation of the system. From this figure it can be noticed that the conduction angle increases linearly from 10° at 38 rpm to a fully open value of 30° at 76 rpm, while the switch-on angle changes non-linearly from 15.5° at 38 rpm to -2.3° at 76 rpm. For any intermediate speed the recommended combination of switching angles can be directly obtained from these two curves of Figure (6).

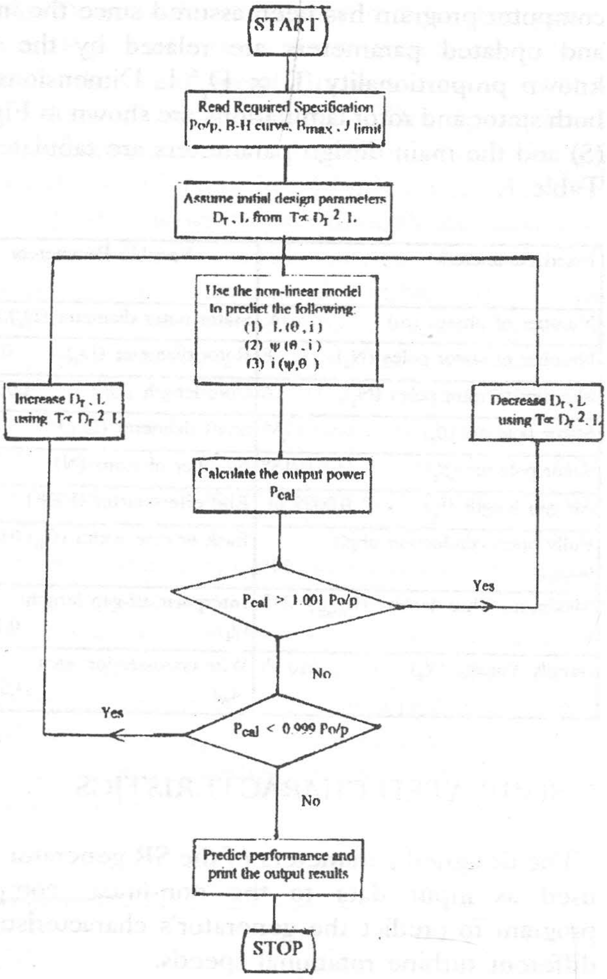

Figure 4. Simplified flow-chart.

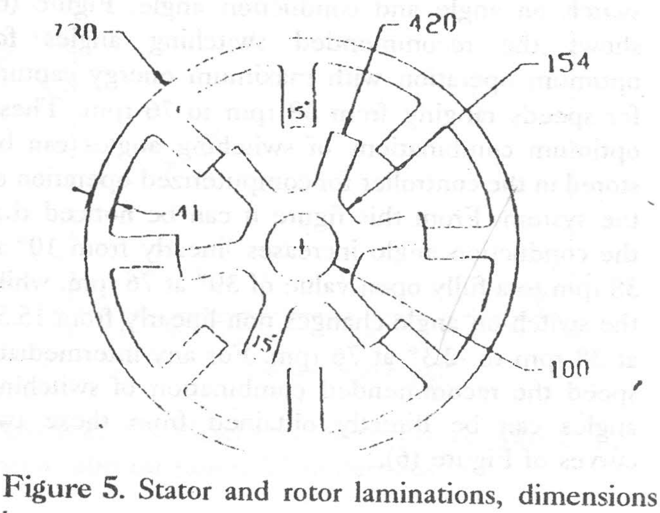

Figure 5. Stator and rotor laminations, dimensions in mm.

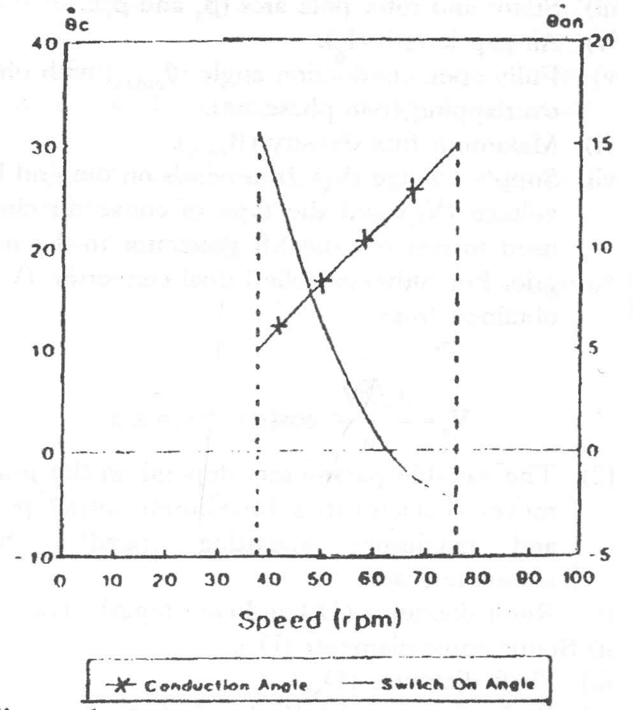

Figure 6. Switching angles variation with rotor speed.

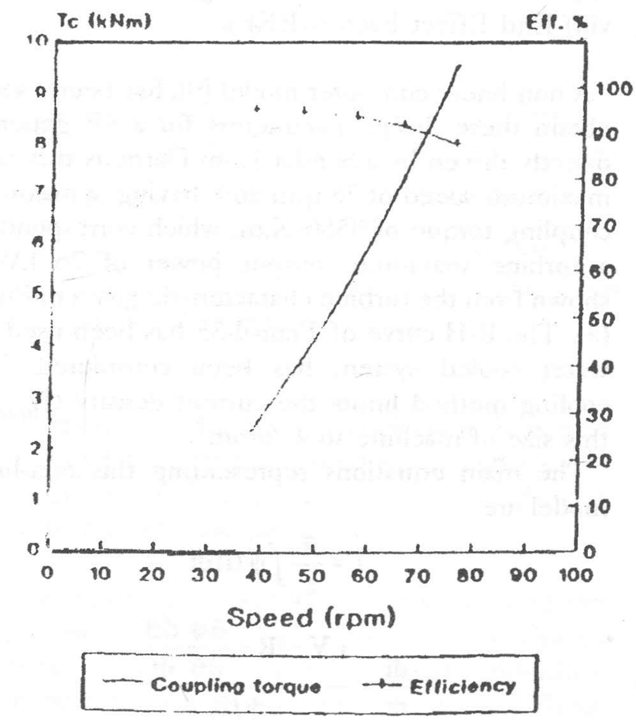

Figure 7. SR generator predicted performance.

Figure (7) confirms that coupling torque is proportional to the square of rotational speed as required for maximum wind energy capture. Also, this figure indicates that the designed SR generator has high efficiencies over the whole working speed range.

To determine the current rating of the main switching devices and the free-wheeling diodes the maximum peak winding current must be determined. Winding current wave forms are shown in Figure (8) for four chosen rotational speeds with switching angles chosen to give the highest peak current at each speed. From this figure the maximum peak current is 157 A at 76 rpm so that a rating of 1000V and 200A is suitable for the switching circuit.

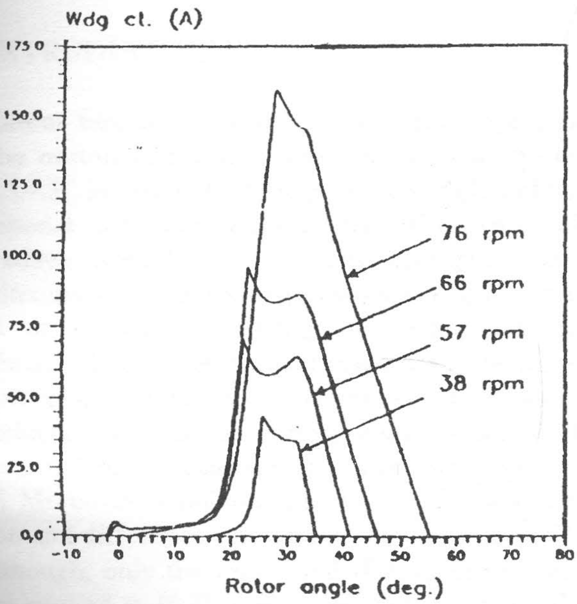

Figure 8. Winding current wave forms.

6. CONCLUSIONS

The study presented in this paper has shown that the output-power/speed characteristic of a switched reluctance generator can match the requirement of maximum energy capture when driven by a variable speed wind turbine. This has been implemented by a relatively simple control system in which switch-on angle and conduction angle are the main parameters. This proposed generating system is connected to the main grid, but it can be used as a stand alone unit to electrical energy to remote areas. It has been demonstrated that the SR generator is suitable for wind applications due to its many advantages such as:

1. Cheap, reliable and maintenance-free;
2. Operates efficiently at low speed, so eliminating the gearbox;
3. Has high efficiencies over the whole operating speed range,
4. It can be operated as a motor to start the Darrieus turbine and as the turbine accelerates to its operating speed, the system can be converted to its generating mode by adjusting its switching angles.

7. REFERENCES

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