Study on Switched Reluctance Generator for Rural Electrification

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ABSTRACT
This paper addresses the need for the utilization of cost effective, maintenance free electric machines in standalone wind energy conversion system meant for rural areas. The suitability of switched reluctance machine as generator for standalone rural wind energy conversion system has been explored through design and analysis. The design process, selection of pertinent topology, static and transient magnetic characteristics has been presented. The suitable topology chosen on the basis of torque to weight ratio estimated from static magnetic characteristics has been subjected to transient analysis to validate the design. Finite element analysis has been extensively used to refine as well as to analyze the finalized design. Vibration analysis also favored the selected switched reluctance generator topology for the economic and maintenance free rural electrification in standalone wind energy conversion systems.

General Terms
Special Electrical Machines, Non-Conventional Energy sources.

Keywords
Finite element analysis, Switched reluctance generator, Wind energy conversion system.

1. INTRODUCTION
The rapid depletion of fossil fuels has necessitated the need for the utilization of non conventional energy sources. Wind energy conversion system is the non polluting energy source suitable for rural areas and the stand alone wind energy conversion system in rural areas must be characterized by economic and maintenance free operation. Doubly fed induction generator (DFIG) suffers from limited rotor converter rating and has problems with over currents during voltage dips and the multistage gearbox that the DFIG must incorporate is unreliable and expensive. The direct coupled variable speed generators for these systems obviate the need for gear box which is the most unreliable and maintenance intensive component in the system. Permanent Magnet Synchronous Generator or Field Wound Synchronous Generator in standalone wind energy conversion systems eliminate the unreliability associated with gear box drive trains through direct coupled variable speed operation and even though permanent magnet machines will have a better torque density than the field wound version, the presence of permanent magnets will make assembly more difficult [1]. In the Field Wound Synchronous Generator, the brushes required to excite the field winding demand maintenance at regular intervals. The variable speed direct drive synchronous generator short falls from cost, size, weight, energy yield and requirement of a converter. Although Permanent magnet generators exhibit low losses, lower weight ,better torque density and perhaps low cost with the disadvantage that the excitation cannot be controlled while axial flux permanent magnet generators are heavier and more expensive than radial flux counterparts. To overcome the afore mentioned obstacles Switched Reluctance Generator (SRG) is being considered as the generator of choice in standalone wind energy conversion systems .The Switched Reluctance Generator (SRG) is characterized by simple and rugged construction [1], [10] and the lack of permanent magnets simplify the assembly, while the absence of brushes on the rotor eliminate the maintenance requirement thus leading to economic operation, a welcome advantage in rural areas. The switched reluctance generator is suited for the prime mover with varying speed and easy to excite as it requires power electronics to operate. In wind energy application, the shaft power is proportional to the cube of the speed, implying a substantial increase in torque and power as the speed increases [1]. The switched reluctance generator does not possess the inherent problem of generating into a shorted winding like a permanent magnet machine thus exhibiting good fault response capabilities. In this paper the design of a switched reluctance generator has been attempted through the design equations that have been presented in a synthesized form. The suitable machine topology is based on low speed operation which is the underlying characteristic in wind energy conversion system and the selection is based on torque to weight ratio [13].Finite element analysis has been extensively employed to study the machine's magnetic behavior whose results aid in the validation of design along with the study of machine's vibration characteristics through the estimation of mode shapes and the corresponding mode frequencies.[13] , [12].

2. SWITCHED RELUCTANCE GENERATOR
Switched reluctance generator is a singly excited, doubly salient machine,[6]. In a switched reluctance generator, mechanical energy is converted to electrical form by proper synchronization of phase currents with rotor position [1], specifically with the declining region of the inductance profile. The geometric model of a 6/4 switched reluctance machine is shown in figure 1.

Figure 1. Geometric model of 6/4 Switched reluctance machine

3. SWITCHED RELUCTANCE GENERATOR DESIGN EQUATIONS

The design equations pertaining to the switched reluctance generator has been presented in a synthesized form [10].The machine that has to be designed has power rating of 20kW with the speed at 100rpm. First the necessary nomenclature has been defined.

m- Number of phases ; N- Number of turns in single stator pole ; In-RMS phase winding current ;D_s-Stator outer diameter ; L_{max}-Aligned inductance; L_{min}-Unaligned inductance ; K_1-Inductance ratio ;λ_{max}- Permeance of air gap at aligned position ; b_S- Width of stator pole ; b_r- Width of rotor pole ;δ- Air gap length ; Z_s- Number of stator ploes ;Z_r- Number of rotor ploes ; α_s – Stator pole pitch ;α_r – Rotor pole pitch ; L_{stk}-Stack length ; K_c – Lamination factor ; μ_o – Permeability of air ;n – Speed of the rotor ; n_N – Rated rotor speed

The parameters of the wind turbine form the input data for the design [12]. The electrical loading of the generator could be expressed as

$$A = \frac{8mDI_n}{\pi D_s} \tag{1}$$

The Inductance value is given by

$$\Delta L = L_{max} - L_{min} \tag{2}$$

Where L_{min} is given by

$$L_{min} = \frac{L_{max}}{K_1} \tag{3}$$

and L_{max} is given by

$$L_{max} = 4N^2\lambda_{max} \tag{4}$$

$$\lambda_{max} = \mu_0 \frac{bl}{\delta} \tag{5}$$

Effective width of stator pole and rotor pole,

$$b = \min(b_r, b_s) \tag{6}$$

The width of the stator pole is,

$$b_s = D_s\cdot\alpha_s\cdot\frac{\pi}{Z_s} \tag{7}$$

The width of the rotor pole is

$$b_r = (D_s - 2\cdot\delta)\cdot\alpha_r\cdot\frac{\pi}{Z_r} \tag{8}$$

The effective length of iron core is

$$l = KL_{stk} \tag{9}$$

The permeance of air gap at aligned position is given by

$$\lambda_{max} = \mu_o\cdot D_s\cdot\alpha_s\cdot\pi\cdot\frac{L_{stk}}{Z_s\cdot\delta} \tag{10}$$

The average torque is given by

$$T_{av} = -\mu_o\cdot\pi^2\cdot(K_1 - 1)\cdot K_c\cdot\alpha_s\cdot A^2\cdot D_s^2\cdot\frac{L_{stk}}{32\cdot m\cdot K_1\cdot Z_s\cdot\delta} \tag{11}$$

Rated average electromagnetic power of the generator is given by

$$P_{em} = T_{av}\cdot 2\cdot\pi\cdot\frac{n_N}{60} \tag{12}$$

The rated output power could be expressed as

$$P_{2N} = \frac{m}{2}\cdot I_m\cdot V \tag{13}$$

$$-P_{em} = K_{em}\cdot P_{2N} \tag{14}$$

Where, K_{em} is the factor of copper loss and core loss. The Number of turns in single stator pole is given by

$$N = \sqrt{\frac{15\cdot K_{em}\cdot K_1\cdot m\cdot Z_s\cdot\delta\cdot V^2}{2\cdot\pi\cdot(K_1 - 1)\cdot\mu_o\cdot\alpha_s\cdot Z_r\cdot K_c\cdot L_{stk}\cdot D_s\cdot P_{2N}\cdot n_N}} \tag{15}$$

4. CONFIGURATION SELECTION THROUGH FINITE ELEMENT ANALYSIS

The voltage equation of a phase can be represented as [12],

$$V = \frac{d\phi}{d\theta}\cdot\frac{d\theta}{dt} \tag{16}$$

Where dθ/dt, is the angular velocity of the machine. Increasing the number of stator poles N_s for a given outer stator diameter and stack length leads to a reduction in the stator and rotor yoke thickness, without leading to higher torque to the same extent ,which tend to increase the core losses also. At low speeds, without changing the number of rotor poles, then the flux will increase and could result in saturation in the iron. This is prevented at low speeds by increasing the number of rotor poles. A high number of poles are therefore used to compensate for a higher rate of rise of flux with angular displacement at low speeds. Hence the apt configurations to be considered are

i. 12/8 configuration
ii. 12/16 configuration
iii. 12/20 configuration

With the torque to weight ratio as the selection criterion, the configuration that yields high torque to weight ratio will be chosen.

4.1 Lamination Data

The evolved design procedure yielded lamination design data as shown in table 1 for the three configurations and the designation for various parts are

Stator diameter - D_s , Rotor diameter - D_r ,Stack length - L_{stk} ,Overall length - L_e , Stator pole width - t_s ,Rotor pole width - t_r , Stator pole depth - d_s , Rotor pole depth - d_r , Stator yoke thickness - y_s ,Rotor yoke thickness - y_r , Air gap – g , No. of stator poles - N_s , No. of stator poles - N_r ,Stator pole arc - β_s , Rotor pole arc - β_r , Shaft diameter - D_{sh}

Table 1. Lamination Data

Dimension	Configuration		
	12/8	12/16	12/20
D_s(m.m)	800	775	760
D_{ag}(m.m)	650	650	650
Y_s(m.m)	30	30	25
Y_r(m.m)	30	30	25
r_{sh}(m.m)	550	450	450
L_{stk}(m.m)	500	350	450
β_s(deg)	8	6	6
β_r(deg)	9	5	4
h_c(m.m)	25	30.6	28
b_c(m.m)	15	13.4	12.8

The average torque has been estimated through finite element analysis [2] and the determination of weight of active parts as shown in tables 2, 3 and 4 helps in the determination of the torque to weight ratio. The weights of active parts have been obtained from the geometry of the machine structure and the physical property of mass density.

Table 2. Weights of Active Parts (12/8)

Parts	**Formula**	**Volume (m^3)**	**Weight (kg) Configuration (12/8)**
Yoke of rotor	$\pi(r_1^2 - r_0^2)L_{stk}$	0.039	295.825
Poles of rotor	$N_r.t_r.d_r.L_{stk}$	1.936X 10^{-3}	14.712
Total rotor	(Yoke +Poles) $_{rotor}$	0.041	310.536
Shaft of rotor	$L_{stk}.\pi.r_{sh}^2$	0.046	335.809
Yoke of stator	$L_{stk}.\pi.(r_3^2 - r_2^2)$	0.044	335.277
Poles of stator	$N_s.t_s.d_s.L_{stk}$	5.402X 10^{-3}	41.054
Total stator	(Yoke +Poles) $_{stator}$	0.05	376.33
Winding	$2 \cdot h_c \cdot b_c \cdot L_{stk} \cdot N_s$	2.998X 10^{-3}	26.86
Total weight	(Stator + Rotor)	0.09	1.07 X 10^3

Table 3. Weights of Active Parts (12/20)

Parts	**Formula**	**Volume (m^3)**	**Weight (kg) (12/20)**
Yoke of rotor	$\pi(r_1^2 - r_0^2)L_{stk}$	0.061	463.346
Poles of rotor	$N_r.t_r.d_r.L_{stk}$	0.014	102.868
Total rotor	(Yoke +Poles) $_{rotor}$	0.075	566.214
Shaft of rotor	$L_{stk}.\pi.r_{sh}^2$	0.072	551.084
Yoke of stator	$L_{stk}.\pi.(r_3^2 - r_2^2)$	0.025	193.609
Poles of stator	$N_s.t_s.d_s.L_{stk}$	4.521X10^{-3}	34.36
Total stator	(Yoke +Poles) $_{stator}$	0.03	227.968
Winding	$2 \cdot h_c \cdot b_c \cdot L_{stk} \cdot N_s$	3.853X10^{-3}	34.52
Total weight	(Stator + Rotor)	0.104	1.38X10^3

Table 4. Weights of active parts (12/16)

Parts	Formula	Volume (m^3)	Weight (kg) (12/16)
Yoke of rotor	$\pi(r_1^2 - r_0^2)L_{stk}$	0.045	339.32
Poles of rotor	$N_r.t_r.d_r.L_{stk}$	6.298X 10^{-3}	47.862
Total rotor	(Yoke +Poles) $_{rotor}$	0.051	387.18
Shaft of rotor	$L_{stk}.\pi.r_{sh}^2$	.0034	259.28
Yoke of stator	$L_{stk}.\pi.(r_3^2 - r_2^2)$	0.025	186.77
Poles of stator	$N_s.t_s.d_s.L_{stk}$	6.029X 10^{-3}	45.818
Total stator	(Yoke +Poles) $_{stator}$	0.031	232.58
Winding	$2 \cdot h_c \cdot b_c \cdot L_{stk} \cdot N_s$	3.432X 10^{-3}	30.749
Total weight	(Stator + Rotor)	0.082	909.81

The 12/16 configuration is seen to posses' better torque to weight ratio as evident from table 5. In a Wind energy conversion system the weight is very important in terms of the torque per weight ratio, even though 12/8 configuration's energy conversion per stroke is large owing to the fact cited above. Moreover if the number of stator poles is fixed ,but the number of rotor poles increased, more circumferential space is available for copper .This allows the radial dimensions such as outside diameter and core back iron to be reduced. However for very high rotor pole numbers the decrease in pole width results in high pole flux densities [3]. The torque characteristic of the 12/16 configuration is shown in figure 2.

Figure.2. Torque characteristics of 12/16 switched reluctance generator

Table 5. Torque to weight ratios

Configuration	Tavg(Nm)	Torque/Weight ratio (Nm/kg)
12/8	1931.276	1.804
12/16	1932.428	2.123
12/20	1901.118	1.377

5. STATIC MAGNETIC CHARACTERIZATION

The geometrical model and the flux lines plot at aligned position for the chosen 12/16 configuration is shown in figures 3 and 4 respectively [4]

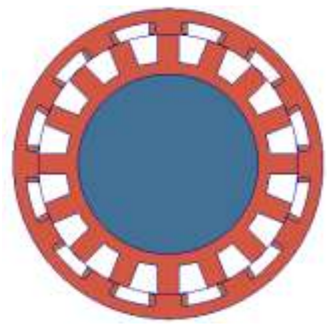

Figure **3. Geometrical model of 12/16 switched generator at aligned position**

Figure 4. Contour plot of 12/16 switched reluctance generator

The finite element model along with torque characteristics for the 12/20 and the 12/8 configurations are shown in figures 5, 6, 7 and 8 and a perusal of the characteristics justify the choice of the 12/16 configuration.

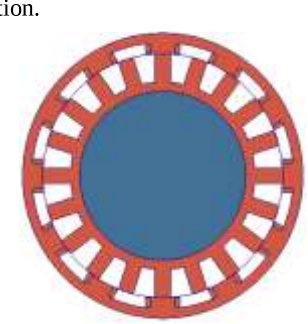

Figure 5. 12/20 configuration- Finite element model

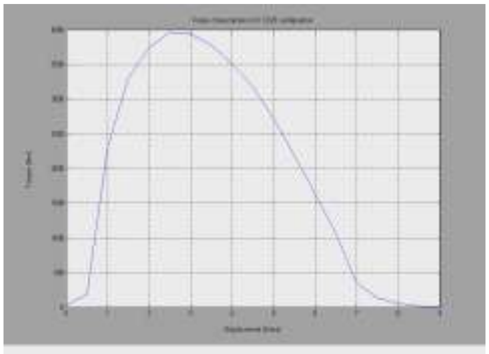

Figure 6. 12/20 configuration - Torque characteristics

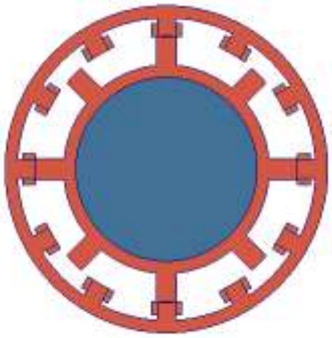

Figure 7. 12/8configuration- Finite element mode

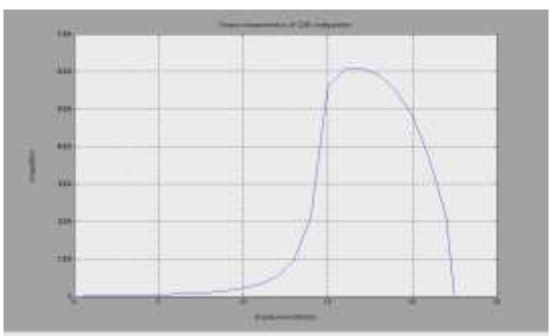

Figure 8. 12/8configuration - Torque characteristics

The combined flux linkage characteristic of the three configurations shown is shown in figure 9.

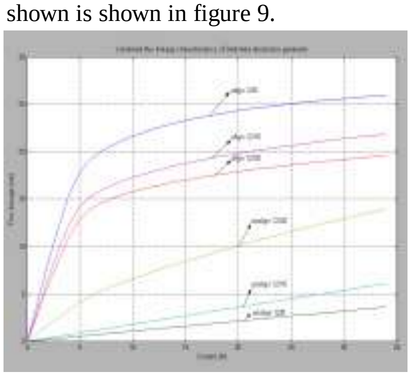

Figure 9. Combined flux linkage characteristics

6. TRANSIENT ANALYSIS

Transient analysis has been carried out with asymmetric half bridge converter, where the power semiconductor switches have been modeled as ideal switches as shown in figure 10

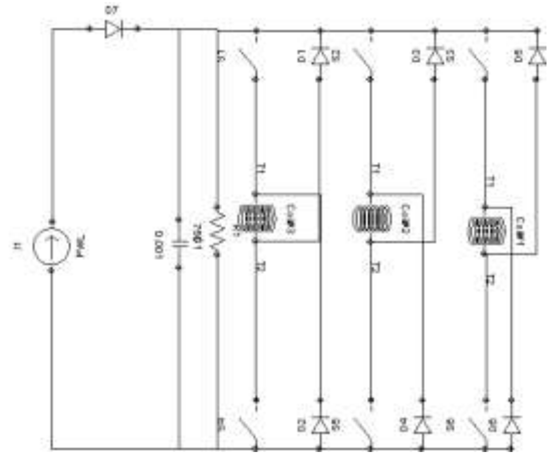

Figure.10. Power converter model for transient analysis

The inductance profile as obtained from transient analysis is shown in figure 11and the corresponding flux linkage variation is portrayed in figure 12.

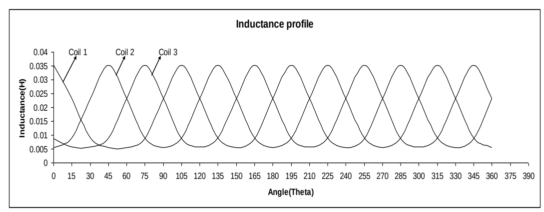

Figure.11. Inductance profile from transient analysis

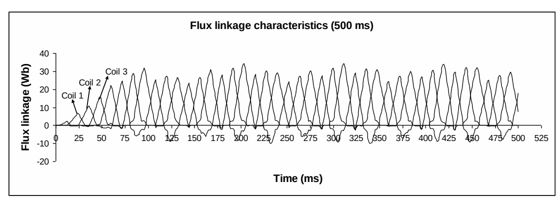

Figure.12. Transient analysis flux linkage characteristics

The excitation capacitor determines the generation of voltage by the switched reluctance machine and the choice here results the voltage and current waveforms as shown in figures 13and 14 respectively

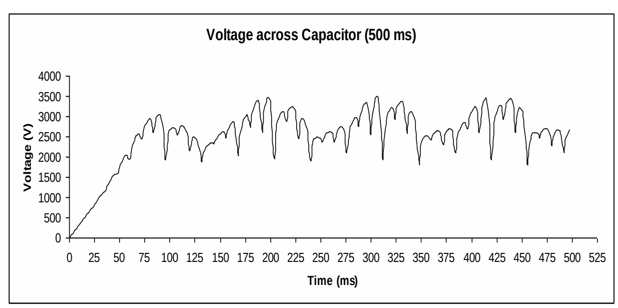

Figure 13. Voltage across the capacitor

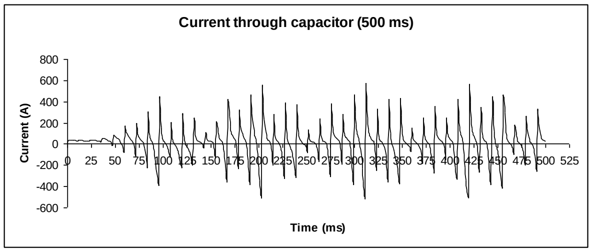

Figure 14. Current waveform

The transient results clearly indicate that the inherent double saliency of switched reluctance generator results voltage waveform with ripples. Pertinent control scheme and fine tuning of power converter design through the application of a well designed filter followed by an inverter will result practical utility voltage waveform.

7. VIBRATION ANALYSIS

In a switched reluctance machine the tangential force is responsible for the reluctance torque but the magnetic flux in the machine also pass across the air gap in radial direction, which exerts a radial force on stator pole and yoke thus results in vibration and acoustic noise [5]. Various studies identified that the dominant noise source is the radial deformation of the stator due to the radial magnetic attraction towards the rotor. The stator of the switched reluctance machine has a natural frequency. When one of the frequencies of the exciting source coincides with the stator natural frequency, due to resonance effect acoustic noise is produced. Modal analysis [7] is used to determine the natural frequencies of the stator structure and the corresponding mode shapes. The loading conditions applicable for this type analysis are Displacement load and Force/movement load. The former loading condition is applied to the machine base, while the latter loading condition is applied across the poles which are excited, as shown in the figure 15.

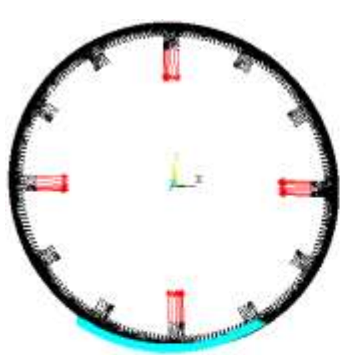

Figure.15. Loading conditions for modal analysis.

The various mode shapes (Eight mode shapes) [8] have been obtained along with their natural frequencies as shown in figure 18. The switching frequency of the converter at the nominal wind speed of 12 m/s can be estimated from the expression

$$fs = \frac{n.Nr}{60} \qquad (17)$$

Where f_s is the power converter switching frequency, n is the rotor speed in rpm and Nr is the number of rotor poles.

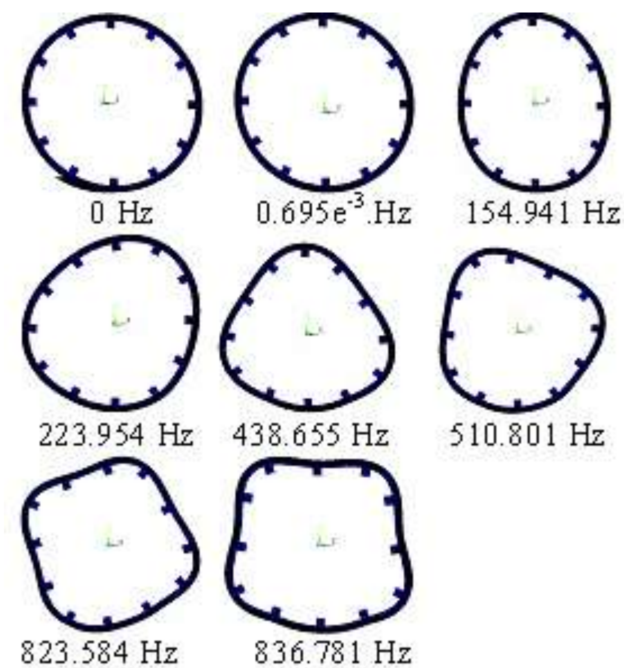

Figure 18. Mode shapes and the natural frequencies

The switching frequency estimated for a wind speed of 12m/s (For the turbine speed of 114. 6 rpm) at the power output of 20kW is given by 30.56 Hz. From the modal analysis it is pellucid that at the operational speed of the wind turbine vibration of the generator is not critical that has to be addressed by special measures.

8. CONCLUSION

This paper assessed the suitability of a switched reluctance generator for a standalone wind energy conversion system meant for rural areas. The suitable topology on the basis of torque to weight ratio estimated from static magnetic characteristics has been subjected to transient analysis to validate the design process. Vibration analysis also favored the selected switched reluctance generator topology for the economic and maintenance free rural electrification in standalone wind energy conversion systems.

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