MINI/MICRO HYDRO ELECTRIC POWER GENERATION USING AN AXIALLY LAMINATED ANISOTROPIC SELF-EXCITED RELUCTANCE GENERATOR

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Abstract: - Energy is key input to drive and improve the life cycle. Due to depletion of fossils fuel, the main source of energy, strongly suggests that harnessing of non conventional, renewable and environment friendly energy resources is vital for steering the global energy supply towards a sustainable path. Mini/micro hydropower is a form of non-depleting, self–replenishing energy that can be harnessed without adversely affecting the environment. To tap this potential self excited reluctance generator may be a better alternative for induction generator. This paper presents a mathematical model of self excited synchronous reluctance generator using Park's transformation. Fabrication and testing of axially laminated anisotropic rotor have been presented in this paper. Performance of self excited reluctance generator has been enhanced by increasing its saliency ratio. The self regulating feature of a self excited reluctance generator is also examined.

Key-Words: - Reluctance machine, saliency ratio, self–excitation, anisotropic, axially laminated rotor

1 Introduction

The whole essence of human civilization is the way natural energy has been harnessed to meet the requirements of human race without causing ecological imbalance. Fossil fuels are the main source of conventional energy. Depletion of conventional energy resources and increasing demand of energy forced the researchers to think over renewable resources of energy e.g. solar, wind, tidal and minor hydro power etc. The ability of induction generator to convert mechanical power to electrical power over a wide range of speed has made them good candidates to replace synchronous machines in such applications. Its other merits are low unit price, brushless rotor, no separate source for excitation, robustness in operation and low maintenance cost etc. However, this machine suffers from variations in frequency and voltage with changes in load. A complex technology is needed to overcome this inherent problem in induction generator which will increase its cost. Reluctance generator offers the solution to the problems faced by induction generator nevertheless it includes almost all the benefits of induction machines.

Reluctance machine have been known as early as induction machines but they have not been developed and exploited until the early sixties[7,8]. The reason for lack of attention in the early days had been due to their poor overall performance compared with well developed squirrel-cage induction machine. But reluctance machine have attracted considerable attention during the last two decades or so, resulting in much improved performance. Various rotor configurations other than salient pole structure were thought over to improve the performance of reluctance machine by increasing the reluctance power. The reluctance power depends upon the saliency ratio(L_d/L_q) of the machine There have been various proposals2 to increase L_d/L_q, resulting in different rotor configuration. All the classes of rotor design aimed at maximizing saliency ratio to provide a flux guide to d-axis flux by increasing Ld and flux barrier to q-axis flux by decreasing Lq. To obtain high saliency ratio two pole axially laminated anisotropic rotor reported1 in recent years is not naturally suitable for a conventional shaft. Expect few works[3-6] recently, little efforts have been done to use reluctance machine as a generator. This paper implements the fabrication and laboratory testing of a practical four pole ALA rotor synchronous reluctance machine (SRM). The stator of reluctance machine with any class of rotor is similar to that of an induction machine. A mathematical model has been presented in this paper to simulate the performance of reluctance generator which is verified by laboratory tests. This paper also introduces the suitable short shunt compensation to obtain a self regulated reluctance generator.

2 SRM as a Self Excited Generator

Self-excitation in isolated reluctance generator is achieved when the rotor is driven by an external primemover and its terminals are connected to a suitable three phase capacitor bank. The process is started by a small amount of EMF induced in the stator by the action of residual flux. This EMF is sufficient to cause a current to circulate in the stator winding. If the proper amount of capacitance has been connected to the machine, the subsequent stator MMF will produce flux in the direction of the residual magnetism thus causing more voltage buildup and a greater current flow. As in all self excited machines, buildup of induced EMF and current will continue until equilibrium is attained by the action of magnetic saturation. This is determined by the balance of real and reactive power flows between the machine, the excitation capacitance and the connected load. A single line diagram of 3-phase self excited reluctance generator is shown in Fig.1. Abdel-Kader[5] developed an equivalent circuit for the reluctance generator in the same manner as the induction generator. The author has not taken care of saliency ratio; an essential parameter which decides the performance of generator. Rahim[3] made a comparison between the steady state performance of induction and reluctance generators.

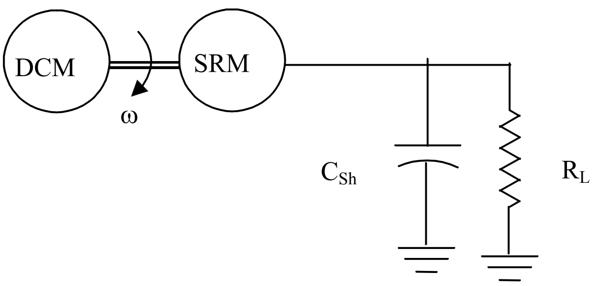


Fig.1Single line diagram of the SERG with resistance load

3 Principle of operation

Electromechanical energy conversion involves the interchange of energy between an electrical system and a mechanical system through the medium of a coupling magnetic field. In case stator winding is excited and rotor is salient pole in structure without any winding, the expression of torque is given by

$$T_{ri} = \frac{1}{2} i_s^2 \frac{dL_{ss}}{d\theta} = -\frac{1}{2}\phi^2 \frac{d\Re_s}{d\theta} \quad \text{-------- (1)}$$

where $\Re s = \frac{\Re_q + \Re_d}{2} - \frac{\Re_q - \Re_d}{2}\cos 2\theta$ and Φ denotes the instantaneous flux produced by the stator mmf Ni_s acting in the path of reluctance $\Re_s$. The negative sign indicates that the direction of the torque is such as to bring about a reduction in reluctance. Therefore, as long as the reluctance of the magnetic circuit, as viewed from the stator, varies for different positions of the rotor, a torque due this reluctance variation exists. Expression for average torque is:

$$T_{r(average)} = \frac{1}{2\Pi}\int_0^{2\Pi} T_{ri}\, d\omega t = \frac{1}{\Pi}\int_0^{\Pi} T_{ri}\, d\omega t$$

If $\omega=\omega_r$ then the expression for the reluctance torque is given by

$$T_{r(average)} = \frac{1}{4}\frac{V^2}{\omega}\frac{x_d - x_q}{x_d x_q}\sin 2\delta \quad \text{------ (2)}$$

Thus the machine is capable of producing an average reluctance torque only when the angular speed of the rotor(ω) is equal to the angular frequency of the stator line current. Furthermore, this torque varies with an argument that is double the torque angle δ. The maximum reluctance torque occurs at $\delta=45^0$.

4 Maximization of saliency ratio

The saliency ratio is the main factor which decides the performance of reluctance machine either as a generator or a motor. In the classical design, three phase reluctance generator analyzed and studied by various authors employed simple salient poles. The power factor and power density of three phase reluctance generator with this conventional salient pole rotor in Fig.2(a) are lower than those for induction generator with an identical stator as the saliency ratio is very small (less than 2). Its efficiency is also very low. Manufacturing simplicity and mechanical strength were the major advantages. Recent design abandoned the traditional poles and various proposal of rotor configuration to increase saliency ratio have been cited in literature[1,2,5] for the improvement of reluctance machine performance. The new segmental rotor in Fig.2(b) gives significant improvement in its power factor, efficiency, and pull out power over conventional salient-pole rotor SRM. A new form of non segmented rotor as in Fig.2(c) has multiple flux barriers for each pole pair. The new rotor is simple to make and it requires no special material. The synchronous performance of this SRM is appreciably superior. Due to difficulty of constructing the multiple barriers from a unitary lamination; attention was given to replace the usual radial lamination by axial lamination of anisotropic material whose permeability was not only directional but also followed a pattern corresponding to the natural shape of the flux lines. The ideal rotor is one which is infinitely permeable along the flux lines and completely impermeable across q-axis. The axially laminated rotor in Fig.2(d) approximates this arrangement reported in few references[1,2] in recent years to achieve high saliency ratio to improve the performance of SRM.

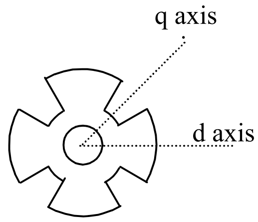


Fig.2 (a) Salient pole rotor

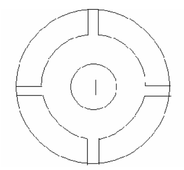


Fig.2 (b) Segmental rotor

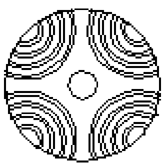


Fig.2 (c) Flux guided rotor

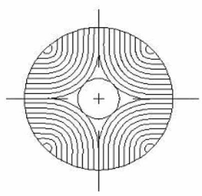


Fig.2 (d) ALA rotor

5 Laboratory machine

A 4-pole ALA rotor reluctance synchronous machine has been designed and fabricated. The cold rolled grain oriented transformer lamination sheet steel and paper insulation between laminations have been used for the construction of ALA rotor. A mild steel shaft has been fabricated according to the motor frame and ball bearings dimensions. Then four semicircular curves on shaft were prepared by milling operation for the axial placement of laminations and insulation alternately. A nonmagnetic nonconducting pole holder was used to firmly hold the axially placed laminations and insulations. Finally, the shaft and the assembly of laminated layers and rotor pole holders are assembled and machined to form smooth rotor. The sectional view of shaft and axially laminated anisotropic rotor is shown in Fig.3. Its design could not be covered in this paper. Its design data is given in appendix.

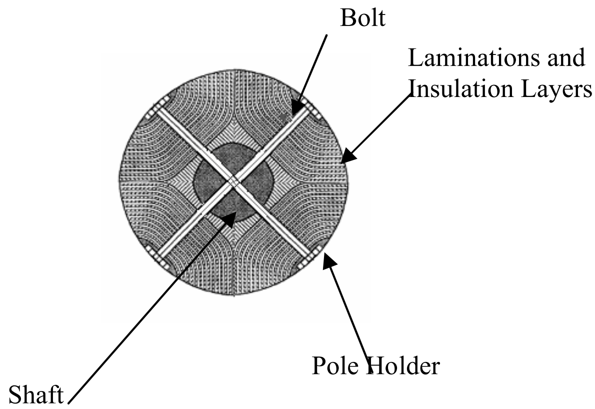


Fig3 Schematic axially laminated rotor

6 Machine model

Three phase voltage equations of SRM in matrix form is expressed as:

$$V_{abcs} = r_s i_{abcs} + p\lambda_{abcs} \qquad \text{---------- (3)}$$

Where $\lambda_{abcs} = L_s i_{abcs}$ p=d/dt

$$L_s = \begin{bmatrix} L_{ls} + L_A + L_B \cos 2\theta_r & -\frac{1}{2}L_A + L_B \cos 2\left(\theta_r - \frac{\Pi}{3}\right) & -\frac{1}{2}L_A + L_B \cos 2\left(\theta_r + \frac{\Pi}{3}\right) \\ -\frac{1}{2}L_A + L_B \cos 2\left(\theta_r - \frac{\Pi}{3}\right) & L_{ls} + L_A + L_B \cos 2\left(\theta_r - \frac{2}{3}\Pi\right) & -\frac{1}{2}L_A + L_B \cos 2\left(\theta_r + \Pi\right) \\ -\frac{1}{2}L_A + L_B \cos 2\left(\theta_r + \frac{\Pi}{3}\right) & -\frac{1}{2}L_A + L_B \cos 2\left(\theta_r + \Pi\right) & L_{ls} + L_A + L_B \cos 2\left(\theta_r + \frac{2}{3}\Pi\right) \end{bmatrix}$$

where L_{ls} is the leakage inductance, L_A is a constant magnetizing inductance, and L_B is the amplitude of the sinusoidal varying magnetizing inductance. For three phase SRM, the stator magnetizing inductance are defined as one and half times the magnetizing inductance of a two phase machine. The relation between phase inductances and d-q inductances in rotor reference frame is given by

$$L_q = L_{ls} + \frac{3}{2}(L_A - L_B) = L_{ls} + L_{mq}$$
$$L_d = L_{ls} + \frac{3}{2}(L_A + L_B) = L_{ls} + L_{md} \qquad \text{---------- (4)}$$

The final mathematical model in rotor reference frame under no load condition of SERG is represented as

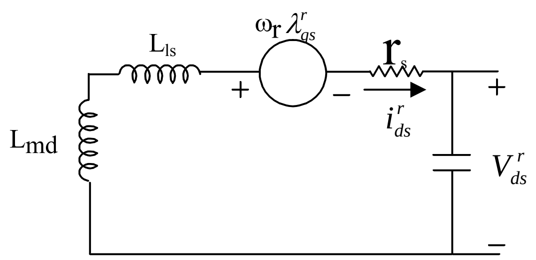
$$\begin{bmatrix} pi_{ds}^r \\ pi_{qs}^r \\ pv_{ds}^r \\ pv_{qs}^r \end{bmatrix} = \begin{bmatrix} \frac{-r_s}{L_d} & \frac{-\omega_r L_q}{L_d} & \frac{-1}{L_d} & 0 \\ \frac{\omega_r L_d}{L_q} & \frac{-r_s}{L_q} & 0 & \frac{-1}{L_q} \\ \frac{1}{C} & 0 & 0 & \omega_r \\ 0 & \frac{1}{C} & -\omega_r & 0 \end{bmatrix} \begin{bmatrix} i_{ds}^r \\ i_{qs}^r \\ v_{ds}^r \\ v_{qs}^r \end{bmatrix}$$

----------- (5)

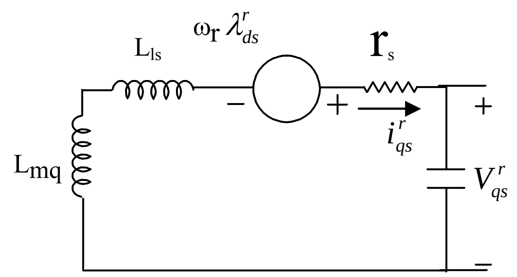
The expression for electromagnetic torque is obtained by expressing i_{as},i_{bs} and i_{cs} in terms of i_{qs} and i_{ds}

$$T_e = \frac{3}{2}\frac{P}{2}(L_d - L_q) i_{ds} i_{qs} \qquad \text{----------- (6)}$$

The d-axis and q-axis operational equivalent circuit of SERG is represented in Fig.4



d-axis operational equivalent circuit



q-axis operational equivalent circuit
Fig.4

7 Steady state analysis

Under steady state and balanced conditions we have p = 0 and the machine phase voltage are equal. The equation (5) reduces to:

$$E = (r_s + x_s)i + V$$

E is resultant air gap voltage given by

$$E = -I_d jX_{md} - I_q X_{mq}$$

The simplified equivalent circuit to obtain steady state performance of SERG is shown in Fig.5

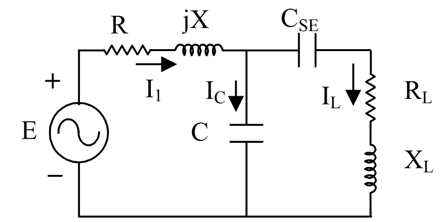


Fig.5 SERG with short shunt compensation

$$V = IZ_{ab} \qquad I_c = \frac{V}{X_C} \qquad I_L = \frac{V}{Z_L}$$

To obtain steady state performance Xmd can be calculated by evaluating R_t, X_t and A for given values of load impedance (R_L+jX_L) excitation capacitance (C_{sh}) and machine parameters. The corresponding air gap voltage E can be determined by experimentally obtained E/X_{md} characteristic at a given speed. Subsequently I_d, I_q and I are evaluated. Then load current I_L, excitation current (I_c), output power (P_{out}) efficiency. Various computed performance characteristics of SERG shown in Figs. (7-12) has been obtained by writing MatLab software code.

8 Results and discussion

The machine used for the tests was originally a three phase four pole 400/230, star/ delta, 50 Hz induction motor. This machine was converted into ALA rotor reluctance machine as described earlier. Three fundamental tests stator resistance test, ac stand still test and synchronous running test are performed to obtain machine parameters. The determined parameters of reluctance machine are given in appendix. Since magnetic saturation is assumed to be confined to the direct axis, only the magnetization curve needs to be known. Magnetization curve is obtained by performing synchronous running test at 1500rpm shown in Fig.6(a). Under this operating condition the input current is assumed equal to direct axis current Id. For simulation it is more appropriate to plot the air gap voltage E vs X_{dm} shown in Fig.6 (b) ignoring the negligible effect of stator resistance. Using piecewise linear approximation, a linear relationship is established as

$$E = \begin{cases} 534.7 - 0.8824 X_{dm} & 130 < X_{dm} < 198 \\ 867.7 - 2564 X_{dm} & 198 < X_{dm} < 237 \\ 2156 - 8 X_{dm} & 237 < X_{dm} < 247 \\ 11707 - 46.74 X_{dm} & 247 < X_{dm} < 250 \\ 0 & 250 < X_{dm} \end{cases}$$

The reluctance generator driven at 1500 rpm by a DC a motor was excited through delta connected capacitors of 16, 20 and 28 µF. The reluctance machine will build up the voltage for a given capacitance if the rotor speed reaches a critical speed, very similar to self excited induction generator. The load consisted of symmetric variable resistors. Performance results were recorded for different excitation capacitance and load condition. The final results are shown in Figs. 7, 8 and 9. The voltage increases with exciter capacitance. The load voltage reduces with load current and both collapses to zero when the load resistance reaches to a very low value as excitation is insufficient. The generator current are reduced (as an overload protection) when the SERG is short circuited as shown in Fig.8. The output power can be increased at higher capacitance. A close agreement between computational and experimental result is found. To improve voltage regulation inclusion of additional series capacitance to provide additional VAR with load is the attractive option. The variation of no load terminal voltage with shunt capacitance is shown in Fig.11 at 1500rpm. As a first approximation, value C_{sh} (20µf) corresponding to no load terminal voltage equal to rated value has been considered. The variation of full load voltage regulation with series capacitance is shown in Fig.12. It reveals that in arrange of series capacitance there is a distinct minimum value of voltage regulation. Further, a close agreement between computed and experimented results can be found.

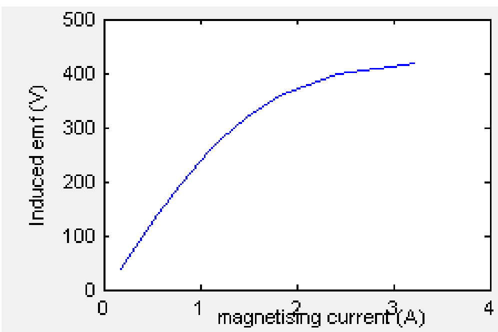


Fig.6(a) Magnetization curve

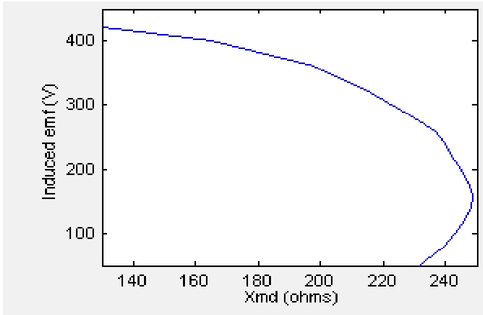


Fig.6(b) Induced emf vs magnetizing reactance

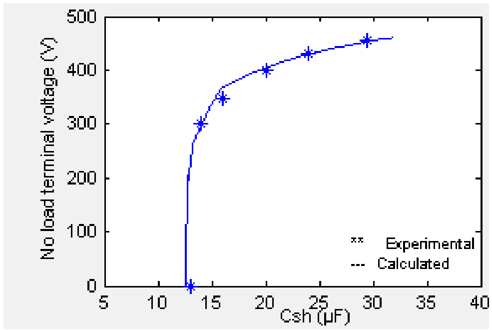


Fig.7 No load voltage vs excitation capacitance

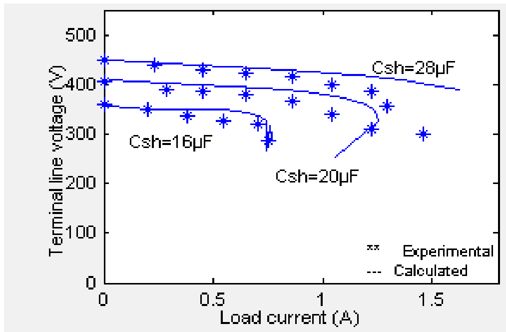


Fig. 8 External characteristics of SERG

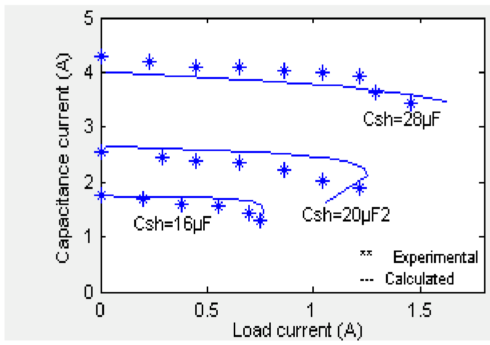


Fig.9 Capacitance current vs load current

9 Conclusion

To harness renewable resources especially micro/mini hydro potential synchronous reluctance generator fitted with axially laminated anisotropic

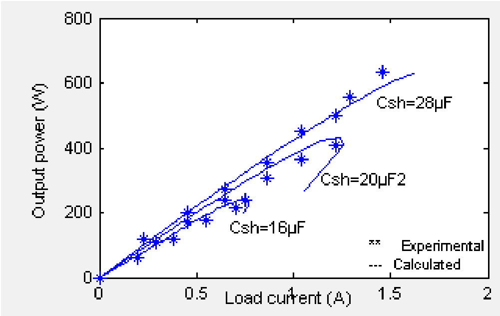


Fig.10 Output power vs load current

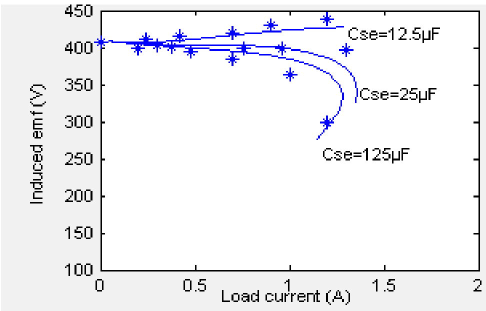


Fig.11 External characteristics with cse

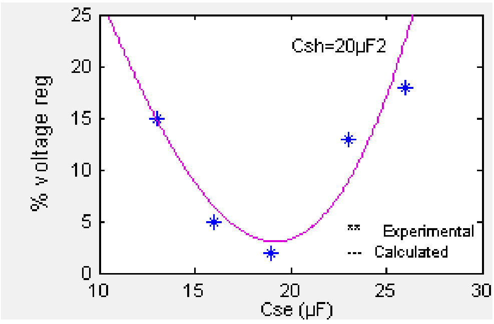


Fig.12 Percent voltage regulation with c_{se}

rotor is found to be better alternative for induction generator. The mathematical model of three phase self excited reluctance generator has been presented using Park's transformation. This model simplifies the simulation to obtain the dynamic as well as steady state performance SERG. To achieve high saliency ratio for obtaining improved performance an axially laminated anisotropic rotor reluctance machine is fabricated. Its performance is given by testing the self excited reluctance generator in laboratory. It is shown that the reluctance machine can be cheap, reliable and robust alternative to self excited induction generator for conversion of non conventional energy sources to electrical energy. The reluctance generator has added advantage of no rotor copper losses due to synchronous operation.

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Appendix: Prototype Motor

Stator:
Number of poles: 4
Rated voltage: 400 V
Rated frequency: 50 Hz
Stack length: 108mm
Inner diameter: 82.54 mm
Type of winding: 3-phase double layer ac armature
Parameters of SERG: Stator resistance r_s =16.5 Ω, Stator leakage reactance X_s =16.5 Ω, X_{qm} =15.55

Rotor:
Air gap: 0.25mm
Number of steel lamination per pole: 20
Steel lamination: CRGO steel 0.3mm
Flux barrier: paper 0.3mm thick