Modeling of synchronous reluctance generator for an isolated wind turbine system

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***Abstract*— This paper proposes an application of synchronous reluctance generator (SyRG) for stand –alone wind turbine system to supply electric power to remote communities. They are robust, simple, and less expensive compared to other types of brushless generators thus an analytical model in the dq reference frame is developed based on very good parameter identificaion including iron losses and saturation. The direct/quadrature inductances were introduced in the model considering no-load and resistive load conditions. A fast method to estimate the minimum capacitance requirement is proposed in order to determine the self-excitation and the required minimum residual rotor magnetism for self-excitation in the reluctance generator connected with capacitances are discussed. The capability of self-excitation in the reluctance generator by connecting charged capacitors is also investigated.**

Keywords — Synchronous reluctance machine (SynRM); Synchronous reluctance generator (SynRG) ; parameters identification;* magnetomotive force.(MMF) ; electromagnetic field (EMF)*; magnetic saturation; iron loss ; self-excited.

I-INTRODUCTION

The electricty demand nowadays makes electrical engineer and reseachers in compulsion to find new kinds of resouces or develops these sources such as wind , biogas and hydroelectric .

Wind energy is one of the prosperous alternative energy resources that can possibly eliminate the energy crisis problem and the environmental issues of conventional electricity generation of today's world [1]. This has also led to rigorous researches on suitable electromechanical energy conversion Devices in such power generation schemes. The induction generator has emerged as an electromechanical energy converter to replace the conventional synchronous machines and many authors have presented comprehensive theoretical analysis of self-excited induction generators as well as generation schemes which incorporate voltage and frequency control [2]

Recently, an alternative electromechanical energy converter, the self-excited reluctance generator, has been considered as a potential candidate as a stand-alone generator driven by wind .The reluctance generator has almost all the advantages of the induction generator, and in addition, the frequency of the output voltage is directly proportional to the rotor speed, hence frequency control *can* be easily achieved by regulating the speed of the primemover.

Some models were built to analyze the performance of the self-excited reluctance generator.

Abdel-Kader attempted to develop an equivalent circuit for the SynRG in the same manner as the SIG[8], but neglecting the effect of the saliency ratio which is essential in the reluctance machine. Mohamadien et al. Developed a model based on Park's dq axes transformation and proved its validity both theoretically and experimentally.[7],

However this paper focused on analytical model in the dq reference frame is developed based on very good parameter identificaion including iron saturation and the direct/quadrature inductances were introduced in a model and the mathemtecal prediction of self excitiation cretria which based on the existence of residual flux which can trigger the voltage build-up process is determined based on the machine's characteristics, and ferromagnetic core material of the machine

II. OPERATING PRINCIPLE

A SynRM is composed by a three phase winding with sinusoidal distribution which is fed by a set of currents to produce a rotating magnetic field in the stator. The rotor is an anisotropic structure, where the magnetic reluctance is minimum along the d-axis and maximum along the q-axis.

The operation of the machine relies on the natural trend of the low reluctance structures (d-axis) to align themselves with the magnetic field. Torque production capability depends (on the difference between the d-axis and q-axis inductances $Ld - Lq$) which is known as saliency. The operating power factor in a SynRM, in a given operating point, depends on the ratio of the d-axis to the q-axis inductances (Ld/Lq)which is known as saliency ratio.

Our study is about types SynRM the axially laminated rotor with air barriers(figure 1), since it offers good saliency ratio with an acceptable manufacturing cost ,The number of flux barriers and their thickness are the parameters that decide the saliency ratio and the performance [3][10].

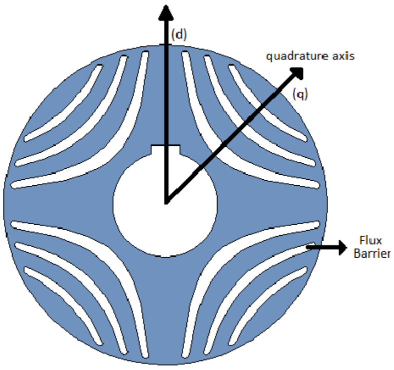

Fig.1 Cross-section and dq axes reference frame of the reluctance machine.

III. THE SYNCHRONOUS RELUCTANCE GENERATOR

A. SynRG Modeling

To get great performant model of this machine we assume that:

1) Space harmonics and time harmonics are neglected.

2) Only the d-axis magnetizing inductance is assumed to be affected by magnetic saturation, while the q-axis inductance is considered to be constant.

$$V_d = R_s i_d - w_e L_q i_{qm} + L_d \frac{di_{dm}}{dt} \quad (1)$$

$$V_q = R_s i_q - w_e L_d i_{dm} + L_q \frac{di_{qm}}{dt} \quad (2)$$

where V_d and V_q are the direct and quadrature axes terminal voltages, i_d and i_q the direct and quadrature axes terminal currents, , i_{dm} and i_{qm} the direct and quadrature axes torque producing currents, L_d and L_q the direct and quadrature axes inductances as a function of i_{dm} and i_{qm} currents, respectively, R_s and R_c the stator resistance and iron loss resistance per phase and , $w_e$is the electrical rotor angular speed.

The electromagnetic torque is stated as:

$$T_e = \frac{3}{2} P \left(L_d - L_q\right) i_{dm} i_{qm} \quad (3)$$

$$T_e = J \frac{dw_m}{dt} + B_m w_m + T_L \quad (4)$$

The torque producing currentsi_{dm} and i_{qm} differ from the stator currentsi_d and $i_q$respectively. The terminal currents $i_d$and i_q can be measured but the torque producing currents i_{dm} and i_{qm}must be calculated. The iron loss resistance R_c is difficult to measure in the transition state. Hence, it is ignored the inductance transition voltage in the steady state, and the relationship between stator currents and torque currents arerepresented as [5]:

$$i_d = i_{dm} - \frac{1}{R_c}\left(w_e L_q i_{qm}\right) \quad (5)$$

$$i_d = i_{qm} - \frac{1}{R_c}\left(w_e L_d i_{dm}\right) \quad (6)$$

Substituting (5) and (6) into (1) and (2), the following voltage equations are obtained:

$$V_d = R_s i_d - w_e \left(1 + \frac{R_s}{R_c}\right) L_q i_{qm} + L_d \frac{di_{dm}}{dt} \quad (7)$$

$$V_q = R_s i_q + w_e \left(1 + \frac{R_s}{R_c}\right) L_d i_{dm} + L_q \frac{di_{qm}}{dt} \quad (8)$$

B.SynRM parameters identification

In order to experimentally determine the SynRM parametrs the iron loss and Ld and the Lq we based on [4] and by this study result the inductances characteristics according to stator current as the shows figure 2 .

An AC voltage is applied across the shorted phases and the other phase winding, while the current is being measured. Using a power meter the reactive power is measured. Thus the reactance and in turn the inductance can be calculated. Since the rotor is locked at the *d*-axis, the current that flows in the winding is the *d*-axis current. The same procedure is repeated for *q*-axis inductance measurement while the rotor is locked at the *q*-axis. In this case the current represents the *q*-axis current.

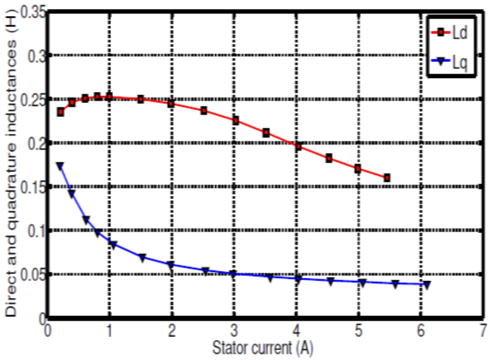

Fig.2. *d* and *q* axes inductances values as a function of SynRM phase current.

C- The self-excitation process

The self-excited generator topology considered here when the speed given to the rotor with a suitable capacitance is connected across the stator terminals. Due to saliency effect, the rotor rotates in synchronism with the armature reaction MMF. and the slip is equal to zero. There is thus the frequency of the output voltage is proportional to the rotor speed.

Anyway to build up its EMF., there must be residual flux in the field poles (residual magnetism) and the excitation capacitance must be larger than some critical value.[2][5], The following figure represent the schematic of self-excited synchronous reluctance generator

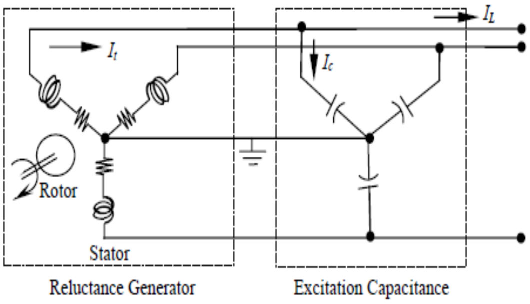

Fig.3. *Schematic of a self-excited synchronous reluctance generator*

D-The minimum capacitance to required the self excitation

To calculate the minimum capacitance we take firstly the equation of the synchronous reluctance generator transformed to Equivalent circuits of the reluctance machine in d-q reference frame.[6][5][9]

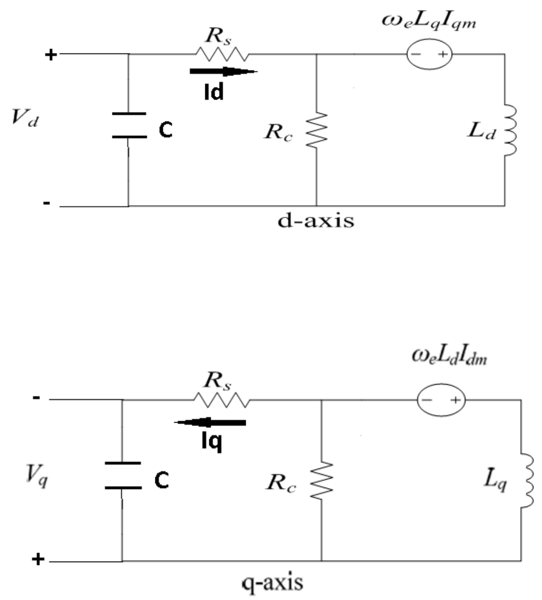

Fig.4.Equivalent circuits of SynRG, considering iron losses, in the rotor reference frame

Secondry We analyse the equation that we took from the equivalent circuit in steady-state performance by reactances.

At no-load condition, the terminals of the reluctance generator are connected to a bank of capacitors. The steady-state voltages results in:

$$V_d = R_s I_d - X_q I_q = -X_c I_q \quad (9)$$

$$V_q = R_s I_q + X_d I_d = X_c I_d \quad (10)$$

where X_d, X_q and X_c are the d-q -axes inductive and capacitive reactances, with $L_d w_e = X_d$, $L_q w_e = X_q$, and $X_c = \frac{1}{C w_e}$. Since the residual magnetism in the rotor is low, it can be neglected in the steady-state analysis.

Firstly, the minimum capacitance required for self-excitation of the reluctance generator is investigated. From (9) and (10), the capacitive reactance is expressed as follows:

$$X_c = \frac{(X_d + X_q) \pm \sqrt{(X_d + X_q)^2 - 4(X_d X_q + R_s^2)}}{2} \quad (11)$$

which indicates that there are two resonant points in the SynG.

Since Xd, Xq and Rs are parameters of the generator which can be known from simulations , it is convenient to obtain the minimum capacitance requirement according to the speed.

As particular case, if Rs is assumed to be zero, Equation (11) is simplified as:

$X_c = X_d$ or $X_c = X_q$

Simply speaking, the resonance conditions are found: the first between Ld and C and the second between Lq and C. Therefore, the required minimum capacitances can be easily related to d- or q-axes inductances:

$$C_{min} = \frac{1}{w_e^2 L_d}. \quad (12)$$

Or

$$C_{min} = \frac{1}{w_e^2 L_q}. \quad (13)$$

Due to the existence of flux barriers, Ld is higher than Lq in the reluctance machine. Consequently, the required minimum capacitances are calculated from d-axis inductance.

V.Results and Disscusion

according to the (7) (8) and the equivalent circuit we have the following equations represent the *dq* model of a SynRG connected in parallel to a capacitor bank :

$$\frac{\mathrm{di}_{\mathrm{dm}}}{dt} = \frac{1}{L_d}\left[-R_s i_d + w_e\left(1 + \frac{R_s}{R_c}\right) L_q i_{qm} + V_d\right]$$

$$\frac{\mathrm{di}_{\mathrm{qm}}}{dt} = \frac{1}{L_q}\left[-R_s i_q - w_e\left(1 + \frac{R_s}{R_c}\right) L_d i_{dm} + V_q\right]$$

$$\frac{\mathrm{dV}_{\mathrm{d}}}{dt} = \frac{1}{C}\left[-i_{dm} - \frac{1}{R_c} w_e L_q i_{qm} + w_e V_q\right]$$

$$\frac{\mathrm{dV}_{\mathrm{d}}}{dt} = \frac{1}{C}\left[-i_{qm} - \frac{1}{R_c} w_e L_d i_{dm} - w_e V_d\right]$$

According to these equations we simulated through Matlab simulink we We got this result in figure 5

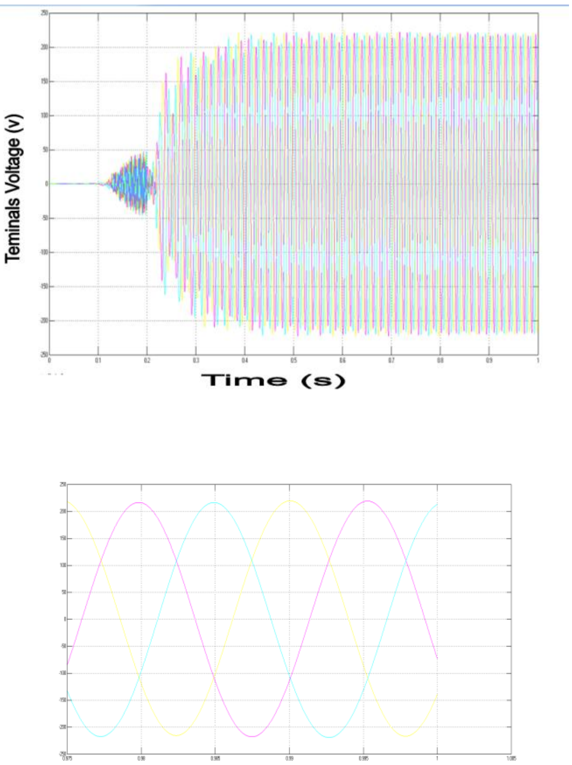

Fig.5.Terminals Voltage

At no-load condition of the SynRG have been carried out. shows the starting process of self-excitation in the reluctance generator at the speed of 1500 rpm. Before t = 0.2 s, the bank of capacitors are disconnected. It is noted that a really insignificant voltage is induced. At t = 0.2 s, the capacitors are suddenly connected to the stator terminals. The generated voltage rises rapidly, until the saturation of the generator. The process of self-excitation is achieved in a very short time.

VI.Conclusion

This paper propses a self excited reluctance synchronous machine for an isolated wind turbine system by determining the minimum value of capacitance . This can not be set without knowledge of the machine parameters.

The obtained simulation results show that a successful self-excitation does not only depend on the presence of a minimum residual flux in the core, but also depends on the acceleration value through which the rated speed of wind turbine is achieved.

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