Operation And Modeling Of Self-Excited Induction Generator Based Standalone Wind Energy Conversion System

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Abstract

This paper concerns an application of a three-phase cage induction machine (IM) as a self-excited generator connected to the ac side of a voltage-source pulse width modulation bidirectional inverter. The generator is supposed to be driven by a wind turbine. The proposed system is intended to be applied in rural plants as a low-cost source of high quality ac sinusoidal regulated voltage with constant frequency. Self-excited induction generator (SEIG) with Static var compensator (STATCOM) supported with battery energy storage system has been presented. As compared to dc link capacitor provided with the STATCOM, battery energy storage improves system stability and prevents power wastage.

1. Introduction

In the literature, it is well known that a three-phase induction machine can be made to work as a self-excited induction generator. When capacitors are connected across the stator terminals of an induction machine, driven by an external prime mover, voltage will be induced at its terminals. The induced electromotive force (EMF) and current in the stator windings will continue to rise until the steady state condition is attained, influenced by the magnetic saturation of the machine. There are two types of induction machine based on the rotor construction namely, squirrel cage type and wound rotor type. Squirrel cage rotor construction is popular because of its ruggedness, lower cost and simplicity of construction and is widely used in stand-alone wind power generation schemes. Wound rotor machine can produce high starting torque and is the preferred choice in grid-connected wind generation scheme [6].

The advantages of using standard three phase squirrel cage induction machine as a self-excited induction generator, SEIG over synchronous alternator are the lower cost due to their simple construction, and the lower maintenance requirements due to their ruggedness and to avoid using brushes. Also, one does not need a separate source for dc excitation current which is required for synchronous alternator. The other advantage is the inherent over load protection. At the occurrence of fault, the current will be limited by the excitation, and the machine voltage will collapse immediately.

Due to the increasing demand on electrical energy and environmental concerns, a considerable amount of effort is being made to generate electricity from renewable sources of energy. The major advantages of using renewable sources are abundance and lack of harmful emissions. Wind is one of the most abundant renewable sources of energy in nature. The wind energy can be harnessed by a wind energy conversion system (WECS), composed of a wind turbine, an electric generator, a power electronic converter and the corresponding control system [1].

2. The Proposed Scheme

The increasing rate of depletion of conventional energy sources has given rise to increased emphasis on renewable energy sources such as wind, micro-hydro, biogas, etc. self-excited induction generator(SEIG) are becoming popular because of their numerous advantages over alternators, specially for wind-generation of electricity in isolated places.

Important parts are available in this system configuration:

- Wind turbine system
- Self-excited induction generator(SEIG)
- Inverter(STATCOM)
- Isolated load

In next part of this paper we will see the modeling of each part and see it’s important in this system configuration.

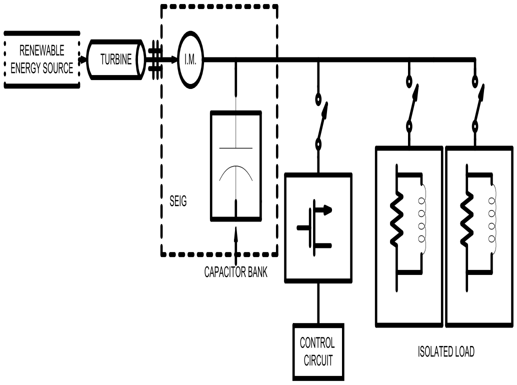


Fig.1 system configuration

3. Wind Turbine

The mechanical power generated by a wind turbine is given by Equation (5).

$$\lambda = \frac{R\omega}{V_w} = Z \qquad (1)$$

$$Y = \frac{1}{\lambda_i} = \left[\left(\frac{1}{\lambda}\right) - 0.035\right] \qquad (2)$$

$$u = e^{(-21*Y)} \qquad (3)$$

$$C_P = (0.5176) * \left((116 * Y) - 5\right) * u + 0.0068 * Z$$

(4)

$$P = \frac{1}{2}\rho C_P A V_w^3 \qquad (5)$$

$$T = \frac{P}{\omega} \qquad (6)$$

P = Mechanical output power of the turbine (W)

C_P= Performance coefficient of the turbine

ρ = Air density (kg/m^3)

A = Turbine swept area (m^2)

V_w = Wind speed (m/s)

λ = Tip speed ratio of the rotor blade tip speed to wind speed

ω_r= angular speed of the turbine shaft

For using Equation (1) to (4) see the relationship between C_P versus λ in Fig. 2.

In fig.2 to fig. 3 are graph of wind turbine generator using Equation (5) and (6). These graphs are generated in the matlab simulation for different-different wind velocity.

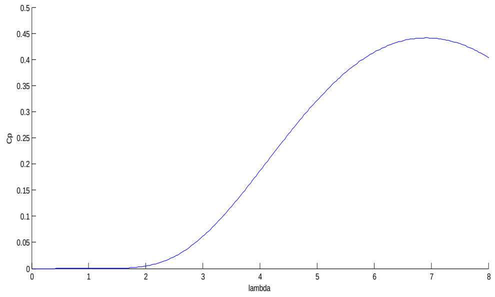


Fig. 2 Relation between Cp versus λ

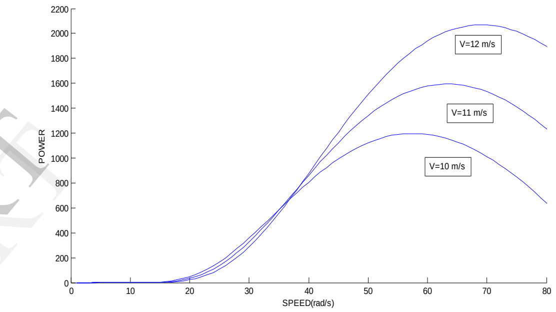


Fig. 3 Relation between wind power and speed

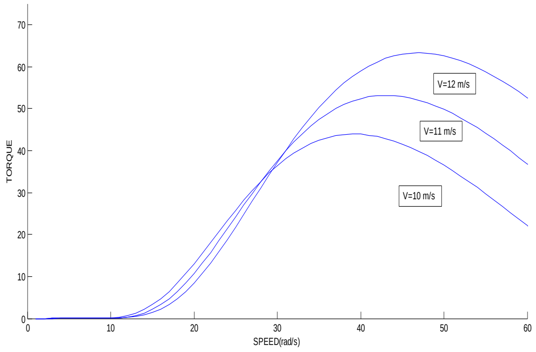


Fig.4 Relation between torque and speed for wind turbine

4. Modeling of Integrated Generating System

The model of the integrated generating system has been developed which is having the following four salient components:

A. Induction Machine
B. Excitation system
C. Load and
D. STATCOM and its equivalent circuit.

A. Modeling of induction machine

The d-q axes diagram of 3-phase symmetrical SEIG with 3-phase balance excitation capacitor and load across its terminals is shown in Fig. 5.

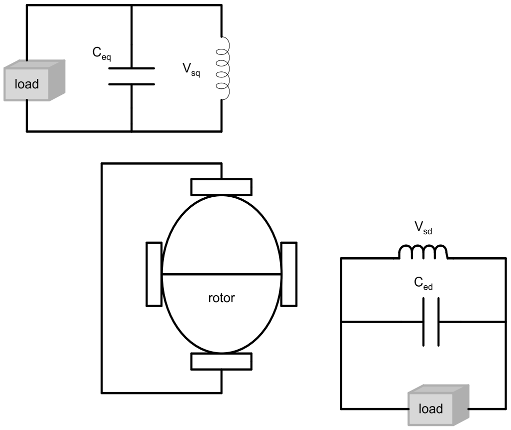


Fig. 5 Schematic d-q axes diagram of SEIG.

The d-q axes equivalent circuit of the 3-phase symmetrical SEIG with a 3-phase balanced excitation capacitor and load across its terminals is shown in Fig. 6.

For the development of induction generator model, the d-q arbitrary reference frame model of induction machine is transformed into stationary reference frame. Using d-q component of the stator currents (i_{sd} & i_{sq}) and rotor currents (i_{rd} & i_{rq}) as state variables, the following differential equations are derived from the equivalent circuit shown in Fig. 6.

$$\frac{di_{sq}}{dt} = \frac{1}{L_s L_r - M^2}\left(-L_r r_s i_{sq} - \omega_r M^2 i_{sd} + M r_r i_{rq} - \omega_r M L_r i_{rd} + L_r v_{sq}\right) \quad (7)$$

$$\frac{di_{sd}}{dt} = \frac{1}{L_s L_r - M^2}\left(-L_r r_s i_{sd} + \omega_r M^2 i_{sq} + M r_r i_{rd} + \omega_r M L_r i_{rq} + L_r v_{sq}\right) \quad (8)$$

$$\frac{di_{rq}}{dt} = \frac{1}{L_s L_r - M^2}\left(-L_s r_r i_{rq} + \omega_r L_s L_r i_{rd} + M r_s i_{sq} + \omega_r M L_s i_{sd} - M v_{sq}\right) \quad (9)$$

$$\frac{di_{rd}}{dt} = \frac{1}{L_s L_r - M^2}\left(-L_s r_r i_{rd} - \omega_r L_s L_r i_{rq} + M r_s i_{sd} - \omega_r M L_s i_{sq} - M v_{sd}\right) \quad (10)$$

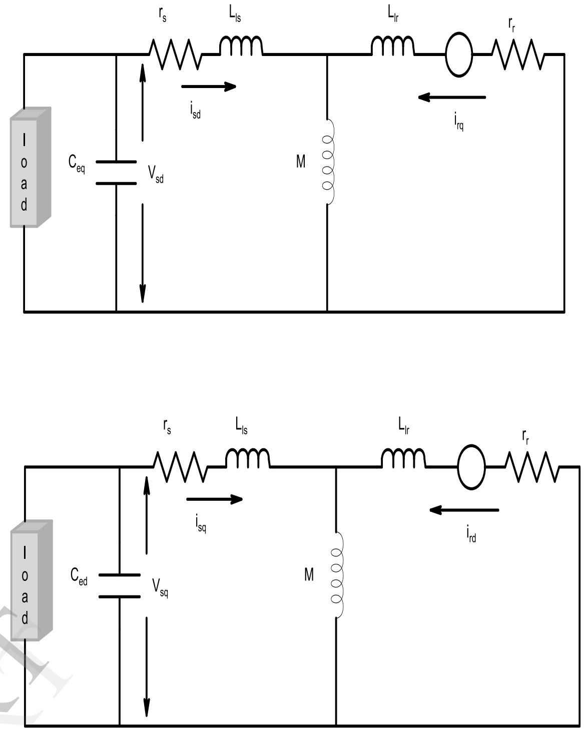


Fig. 6 Equivalent circuit of the Induction Generator in d-q axes stationary reference frame

$$\lambda_{sq} = L_s i_{sq} + M i_{sd} \quad (11)$$

$$\lambda_{sd} = L_s i_{sd} + M i_{sq} \quad (12)$$

$$L_s = L_{ls} + M \quad (13)$$

$$L_r = L_{lr} + M \quad (14)$$

The electromagnetic torque can be computed as a function of q and d axes stator and rotor current as:

$$T_e = \frac{3}{2}\left[\frac{P}{2}\right] M\left[i_{sq} i_{rd} - i_{sd} i_{rq}\right] \quad (15)$$

Where,

Subscripts q and d are for quadrature and direct axes;

Subscript l for leakage component;

Subscripts s and r are for stator and rotor variables;

v and i – instantaneous voltage and current;

i_m – magnetizing current;

λ – flux linkage;

r – resistance;

M – magnetizing inductance;

L – inductance;

P – number of pole;

ω_r – electrical rotor speed;

B. Modeling of Excitation System

The excitation system introduces the following state equations using d-q components of stator voltage (v_{sd} & v_{sq}) as state variables, from the circuit shown in Fig. 6.

$$\frac{dv_{sq}}{dt} = \frac{i_{cq}}{C_{eq}} \tag{16}$$

$$\frac{dv_{sd}}{dt} = \frac{i_{cd}}{C_{ed}} \tag{17}$$

Where C_{eq} and C_{ed} are the excitation capacitor values along with q and d axes.

C. Modeling of Load

The d and q axes current equations for balanced resistive load can be given by:

$$i_{RLq} = \frac{v_{sq}}{R_L} \tag{18}$$

$$i_{RLd} = \frac{v_{sd}}{R_L} \qquad (19)$$

Where R_L is load resistance.

D. Modeling of STATCOM

As mentioned earlier the STATCOM consists of 3-phase voltage source pulse width modulated bi-directional inverter having a bank of battery at the DC bus, which is used to absorb or supply active power between the AC bus and the STATCOM according to the value of modulation index ‘m ‘ and phase angle ‘δ’ between the fundamental component of STATCOM and SEIG voltages. The output terminals of the STATCOM are connected through a coupling transformer having leakage inductance X_s forms the first order low pass filter, which minimizes the current harmonics inducted to SEIG terminals.

For the development of STATCOM model, the d-q arbitrary reference frame model of STATCOM is transformed into stationary reference frame. Using d-q component of the STATCOM currents as state variables, the following differential equations are derived from the circuit shown in Fig. 7.

$$\frac{d_{icq}}{dt} = -\frac{R_c}{L_c} i_{icq} - \frac{mk\,V_{DC}\sin(-\delta)}{L_c} + \frac{v_{sq}}{L_c} \qquad (19)$$

$$\frac{d_{icd}}{dt} = -\frac{R_c}{L_c} i_{icd} - \frac{mk\,V_{DC}\cos(-\delta)}{L_c} + \frac{v_{sd}}{L_c} \tag{20}$$

Where,

i_c – subscripts for current through coupling inductance;

V_{DC} – D.C battery voltage;

V_{AC} – SEIG per phase terminal voltage;

V_{PWM} – fundamental component of STATCOM per phase voltage;

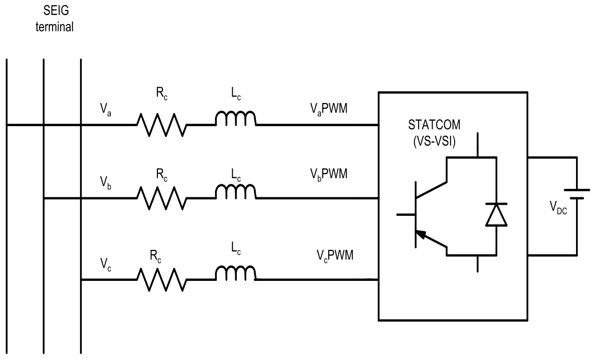


Fig. 7 STATCOM with battery energy storage system connected to SEIG terminals.

R_c – resistance of coupling inductance;

L_c – coupling inductance;

m – modulation index of the PWM inverter;

k – coupling transformer turns ratio;

δ – phase angle between the voltages

At ‘δ’=0, the value of ‘m’, at which STATCOM does not draw any active and reactive power from the PCC. This value of ‘m’ is called critical of ‘m_{cril}’.

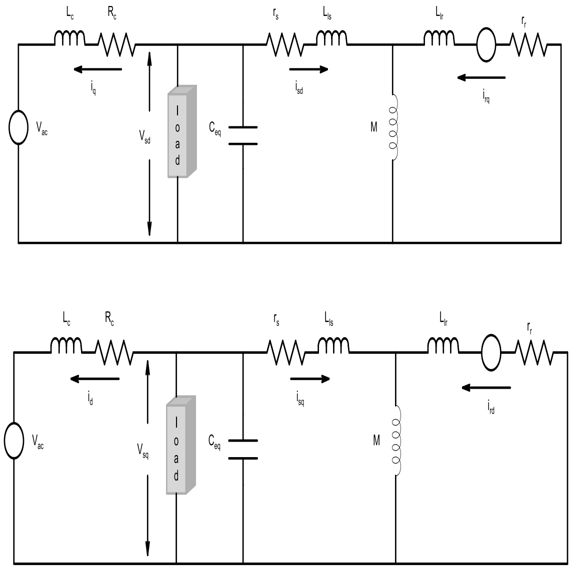


Fig. 8 q-d axis equivalent circuit of SEIG with STATCOM

5. Simulation Results

In Fig 10 are representing the waveform of generated voltage and machine torque at different value of capacitor bank. For SEIG capacitor bank provide a reactive power to the machine to work as a generator and see the change in Fig 10. In this model induction machine is used. And saturation graph of the machine see in Fig 9. See the rating of induction machine in appendix.

Fig. 9 is relationship between no load voltage and current. In induction machine this saturation limit take as linear but in generator cannot take as linear.

In Fig.10 I conclude that the value of capacitance increases, generated voltage and torque are decreases. And also change the time of generated voltage.

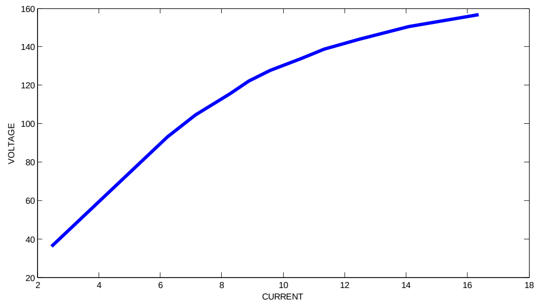
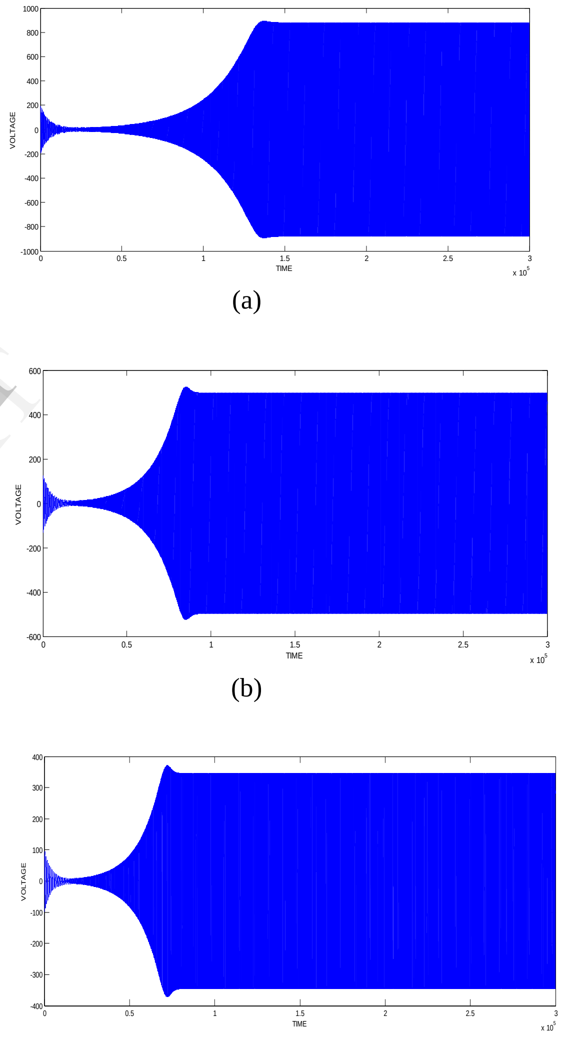


Fig. 9 Saturation graph of SEIG



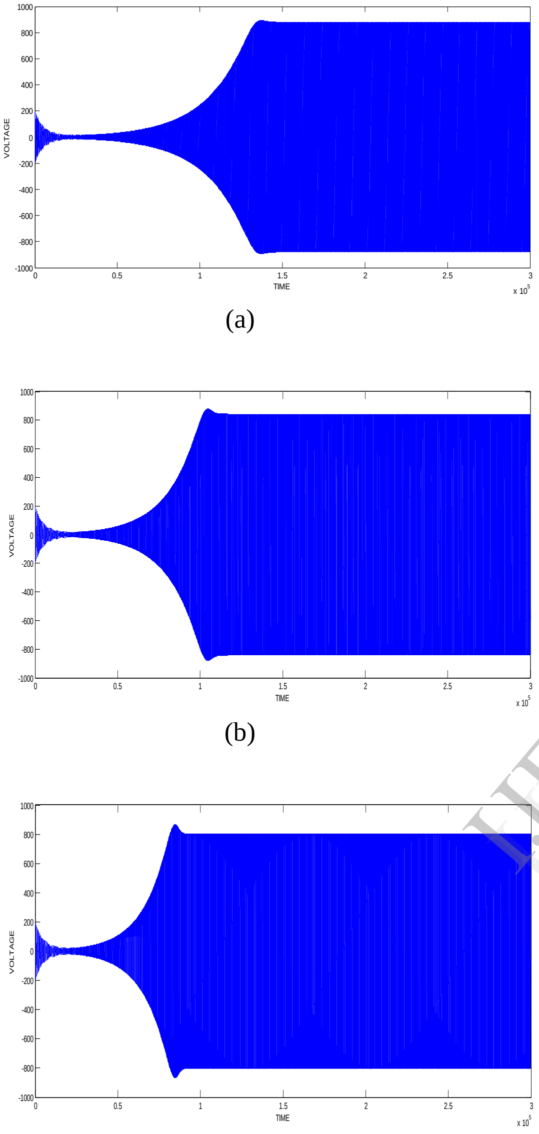
(a)

(b)

(c)

Fig. 10 Generated voltage of SEIG for (a) 200 µF (b) 300 µF (c) 400 µF with no load

In Fig. 11 are representing the waveform of generated voltage and machine torque at different value of rotor speed. In matlab speed model is used as a induction machine.



(a)

(b)

(c)

Fig. 11 generated voltage of SEIG for (a) 1815 rpm (b) 1830 rpm (c) 1845 rpm with no load

In Fig. 11 I conclude that the value of rotor speed increases, generated voltage and torque are decreases. And also change the time of generated voltage.

I used a open loop of control system so use proper control scheme the synchronization of converter and SEIG become near to ideal. No transients are produce see in Fig. 12 STATCOM applied after 4 sec. I set the frequency is 50 Hz and generated voltage is set around 230 V rms. And specification and parameter of induction machine see in appendix.

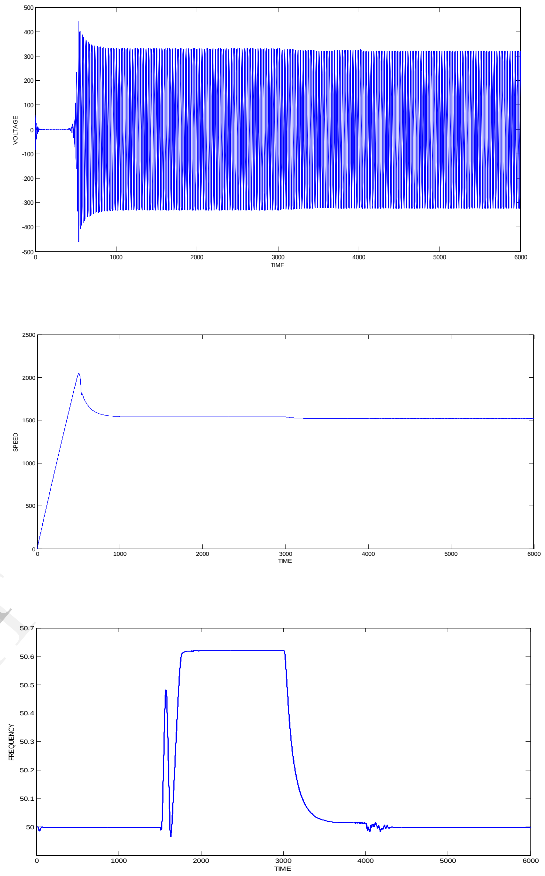


Fig. 12 SEIG with proper RL load after 3 sec and STATCOM after 4 sec

6. Conclusions

Many important and interesting aspects of an isolated self-excited induction generator have been discussed and presented in this paper. The study comprises theoretical analysis and simulation to induction generators. The modeling and characteristics of induction machines in general has been presented to provide an overall perspective of induction generator. Increasing the capacitance value can compensate for the voltage drop due to loading but drop in frequency can be compensated only by increasing the speed of the rotor. For an isolated self-excited induction generator driven by a wind turbine the characteristics of the output power and torque of the wind turbine are important. The output power and torque of a wind turbine drop at high turbine angular rotor speed.

7. Appendix

INDUCTION MACHINE-1

Specification: - Δ-connected, squirrel-cage, speed input, 5595 VA, 230 V, 4-pole, 60 Hz

Parameters: - R_s=0.195Ω, R_r=0.177Ω, L_{ls}=0.001313 H, L_{lr}=0.001969 H

INDUCTION MACHINE-2

Specification: - Δ-connected, squirrel-cage, torque input, 5595 VA, 230 V, 4-pole, 50 Hz

Parameters: - R_s=0.5 Ω, R_r=0.5 Ω, L_{ls}=0.004 H, L_{lr}=0.004 H

8. References

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