Controlled performance of a wind driven self-excited induction generator

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This work addresses the problem of a variable speed wind driven induction generator systems. A Self-Excited Induction Generator, (SEIG), based on a static VAR compensator is investigated. The static VAR compensator is used to control the magnetizing VARs needed by the generator and improve its power factor. The implemented method of SEIG depends on controlling the introduced excitation to the generator by a hysteresis controlled pulse width modulated, PWM, inverter through an inductor in parallel with the induction generator. The model of the Induction Generator, (IG), with a capacitor bank across it is presented. The simulation of the SEIG system is performed where the effects of loading and speed variation are considered. Also the effect of proportional controller gain and the hystersis band width on the output voltage are assessed. The system shows a perfect performance resulting in a constant output voltage apart from any variation in the speed or the load.

يقدم البحث الحالي النمذجة والتحكم في المولدات الحثية ذاتية الإثارة المدارة بواسطة طاقة الرياح. فقد قدم نموذج للمولد الحثي ذو الإثارة الذاتية، وقد تم محاكاة تأثير التغير في سرعة الرياح والتحميل علي الجهد. كما تمت مناقشة نظرية معوض القدرة الغير فاعلة الاستاتيكي للتحكم في الفولت أمبير الغير فاعل الذي يحتاجه المولد الحثي، وقد تم التحكم باستخدام قلاب من نوع "المعدل لعرض النبضة" ويتم التحكم في القلاب بالطريقة التخلفية، ويكون خارج المنظومة ذو جودة طاقة عالية ويمكن تثبيت التردد باستخدام منظومة الموحد والقلاب.

Keywords: Induction generator, Self-excitation, Static VAR compensation, Speed variation, Load variation, Hysteresis control

1. Introduction

Nowadays, the energy related problems that hit the headlines most often are environmental ones. Excessive usage of fossil fuels has led to serious problems, for example global warming, acid rains and oil pollution of the seas. The great opposition facing the nuclear energy in some countries, along with the aforementioned factors have spur researchers attentions for renewable energy. Besides being clean and of low running cost, renewable energy possesses the privilege of abundance and can be used wherever available. Wind Energy Conversion (WEC) system can feed the generated power directly into the grid or use it to feed an isolated load. Traditionally dc and synchronous generators have been used for stand-alone micro-power system. However due to their construction complexity, high cost and maintenance needed, the Induction Generator (IG) is proposed as alternatives to the aforementioned generators. The well known cheapness, rigidity and maintenance ease of the squirrel cage (IG) make it suitable for wind turbines operation. Moreover the squirrel cage IG can tolerate great exposure to hard weather elements which is critical for successful operation in remote locations. They range in size from few kilowatts to over 10 MW. The IGs are suitable for grid connected as well as stand alone applications. In the grid connected case, the excitation current to the IG is supplied through the grid. The rotor speed is maintained above the synchronous speed by mechanical arrangement. In stand-alone or self-excitation mode, the excitation current is introduced by a local source. The use of capacitor bank connected across the IG is the easiest way of having self-excitation. The excitation capacitor value can be altered to regulate the output voltage irrespective of the speed or load variations.

Static VAR Compensator (SVC) has been used to control and improve the performance of self-Excited Induction Generator (SEIG). Several SVC methods have been proposed. The oldest method is to control the excitation capacitance by switching a capacitor bank or using Thyristor Controlled Reactor (TCR) [1]. This method shows a poor transient response as well as introducing harmonics into the system. The use of the PWM converter as a self-excited IG controller is reported in [2]. The PWM inverter can be used as a variable capacitor, accommodating inductive reactance from the generator and the load. The required excitation can be controlled by the modulation index and phase synchronization with the generated voltage.

Considering the fuzzy logic controller proposed in [3], it consists of a two-stage PWM based on ac-dc-ac link. Having required two PWM converters, the installation cost is high. A two-stage PWM controller is also reported in [4,5].

A high performance reactive power compensator is presented and analyzed in [6]. The VAR compensator consists of a three phase current regulated PWM voltage source inverter connected to a controlled dc bus. Reactive power compensation is achieved by forcing the inverter current to follow a reactive sinusoidal reference waveform at a constant switching frequency. The proposed model may need either leading or lagging reactive power compensation with fast current response below half a cycle of the ac supply. The major advantage of this scheme is that the reduced stress on the switching devices as compared with other current regulated techniques. Further it has fast time response, which allows almost instantaneous reactive current control and low harmonic distortion in the line current. A SEIG controller based on SVC with supply current sensing is proposed in [7] with the aim of being used for variable-speed, constant-voltage operations. This control method is independent of the rotor speed. Hence no rotor position sensing is needed. Only two Hall-effect current sensors are required. So far this method can be considered the best one as it allows a constant terminal voltage which is suitable for loads such as lighting, heating and similar. The Wekhande model [7] is implemented in the paper with simulation results showing that this method results in desired performance.

2. Machine Model

The IG in its standard form is an induction machine with a capacitor bank across its stator terminals for excitation purpose. The voltage equations of the induction machine in arbitrary rotating reference frame using Krause transformation [8] are:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & \omega L_s & pM & \omega M \\ -\omega L_s & R_s + pL_s & -\omega M & pM \\ pM & (\omega - \omega_r)M & R_r + pL_r & (\omega - \omega_r)L_r \\ (\omega_r - \omega)M & pM & (\omega_r - \omega)L_r & R_r + pL_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} . \tag{1}$$

With a capacitor bank properly connected across the IG stator terminals, where:

R_s	is the stator resistance per phase
R_r	is the rotor resistance per phase
L_s	is the stator self inductance
L_r	is the rotor self inductance
Ω	is the d-q axes angular velocity
ω_r	is the rotor angular velocity
λ_{dr},λ_q	are the d- and q-axis rotor flux linkage, respectively,
i_{ds}, i_{qs}	are the d- and q-axis stator current ,
v_{ds}, v_{qs}	are the d- and q-axis stator voltage,
v_{dr}, v_{qr}	are the d- and q-axis stator voltage, and
M	is the mutual inductance between rotor and stator.

The capacitor voltage-current equations using Krause transformation [8] are:

$$\begin{bmatrix} i_{qc} \\ i_{dc} \end{bmatrix} = \begin{bmatrix} pC & \omega C \\ -\omega C & pC \end{bmatrix} \begin{bmatrix} v_{qs} \\ v_{ds} \end{bmatrix} , \tag{2}$$

where C is the capacitance/phase in Farads.

A stationary reference frame $\omega=0$ is considered for convenience. The rotor speed, ω_r, is taken as a state variable, the system eqs. (1) and (2) become:

$$v_{qs} = R_s i_{qs} + pL_s i_{qs} + pMi_{qr}\,, \tag{3-a}$$

$$v_{ds} = R_s i_{ds} + pL_s i_{ds} + pMi_{dr}\,, \tag{3-b}$$

$$v_{qr} = pMi_{qs} + R_r i_{qr} + pL_r i_{qr} - \omega_r M i_{ds} - \omega_r L_r i_{dr}, \tag{3-c}$$

$$v_{dr} = \omega_r M i_{qs} + pMi_{ds} + \omega_r L_r i_{qr} + R_r i_{dr} + pL_r i_{dr}, \tag{3-d}$$

$$i_{qc} = pCv_{qs}, \tag{3-e}$$

$$i_{dc} = pCv_{ds}\,, \tag{3-f}$$

where all the parameters are assumed constant and independent of magnetic saturation, except the magnetizing reactance X_M which is a function of M.

3. System simulation

The machine used in this work was 2.2kW, 380V, 5.2 A, 1415 rpm, 50 Hz, three phase star connected squirrel cage induction machine having the following parameters:

$R_s = 8.62\Omega$ $R_r^` = 6.94\Omega$,

$X_s = 9.18\Omega$ $X_r^` = 9.18\Omega$,

$X_M = 282.61\Omega$ (unsaturated value),

The proposed Wekhande model [7] is shown in fig. 1; a wind turbine drives the IG. The two line currents, I_{as} and I_{bs} are measured. Considering a balanced load, I_{cs} is calculated from:

$I_{cs} = -\ (I_{as} + I_{bs})$.

The peak output voltage, V_{max} of the IG is compared with the reference output voltage $V_{AC/ref}$ and the error is multiplied by a cosine wave obtained from the sin/cosine generator. The inverter dc link is considered constant by assuming a constant voltage battery with voltage *dc*, hence the *dc* error is zero. The multiplier output is fed to a proportional controller to generate the reference currents. The three line currents are compared with the reference currents ($I_{as/ref}$, $I_{bs/ref}$ $I_{cs/ref}$) through a hystersis controller. Then the hystersis produces the gate signals of the PWM inverter. The output voltage of the inverter produces the required excitation current to maintain a constant output voltage of the generator.

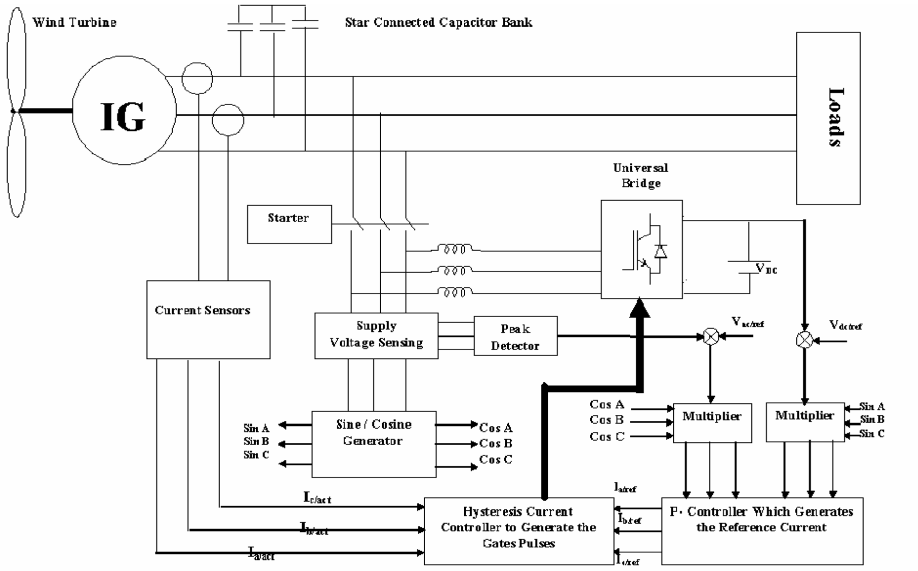

Fig. 1. Block diagram af a voltage controlled wind driven IG.

3.1. Response to speed variation

Upon simulating the considered system using Matlab/Simulink package, the inverter is switched on at t = 2 seconds. Therefore the mutual inductance, M, of the IG is experienced a sudden pulse as a result of the sudden change of the magnetizing current. Then it reaches to its steady state value. However this change in the mutual inductances leads to a sudden surge in the phase voltage before it fads quickly and back to its steady state value of 265 volts. This is demonstrated in fig. 2 and 3.

A ramp drop of speed by 10 rad/sec during 0.1 second is introduced to the system at t = 2.4 sec. A voltage drop transiently takes place before the inverter is able to feed enough magnetizing VARs in order to restore the reference voltage. The effects of speed variation on the output voltage with and without the controller are shown in fig. 3. It is obvious that the hystersis controller prevents the system from experiencing a sever voltage drop when the speed falls down below the rated speed.

3.2. Response of the load variation

When a sudden load is introduced to the system, the IG voltage undergoes a sudden drop. The drop decreases gradually till the voltage is back to the steady state value. This is due to the magnetizing VARs which are fed to the generator thorough the inductor. Fig. 4 shows the load voltage variation and the compensation which restores the initial value of the mutual inductance M. It is clear that the sudden loading of the system has no effect on the output voltage because of the presence of the controlled SVC. On the other hand, the absence of the controller would have a sever voltage drop.

3.3. Response for variation of the hystresis band and the proportional controller gain

The variation of the proportional gain Kp causes undesirable effect in the output voltage. The ideal range of Kp is between 0.001 and 0.01. Having decreased its value below the minimum value, it results in inability of a hysteresis controller to operate

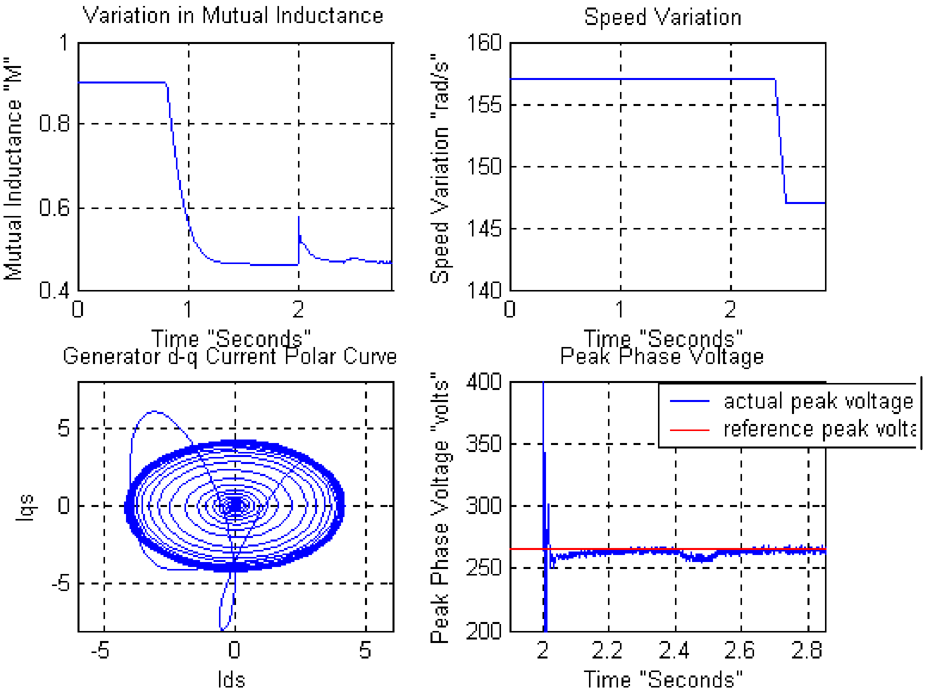

Fig. 2. Variation in the mutual inductance, speed and peak voltage upon the introduction of the inverter and the variation of the speed.

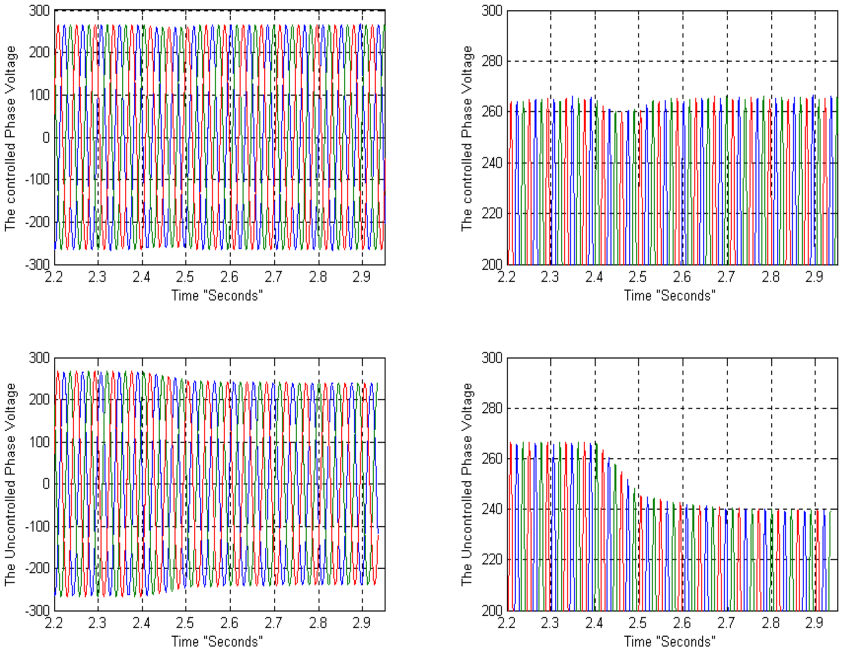

Fig. 3. Variation in the phase voltage upon the introduction of the inverter and variation of speed.

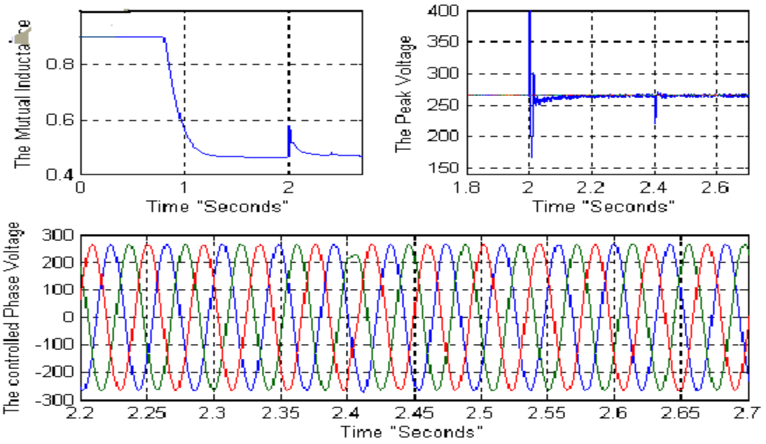

Fig. 4. Phase voltage variation upon the introduction of a sudden load.

properly. Hence the inverter will not feed the required VAR and the output voltage will not be able to attain the reference value, fig. 5. Increasing *Kp* above the maximum value leads to saturation in the control effort of the controller, and the generator produces *dc* output as shown in fig. 5.

Decreasing the value of hystersis band, *ΔH*, gives a better response in terms of smaller error and more accurate output voltage. But this comes at a price of higher switching frequency causing switching harmonics in the output voltage. Increasing *ΔH* above a certain limit causes a system bad response. This was due to a large allowed error tolerance. Hence the output voltage will not be in an acceptable range. Moreover the inverter will not be able to respond quickly enough to speed and load variations. Fig. 6 shows the effect of ΔH variation on the output voltage.

4. Conclusions

This paper studied the voltage control of SEIG. The system is implemented using Matlab/Simulink pakage. The simulation was carried out to show the effect of load and speed variation on the output voltage. The effects of the hystersis band width ΔH and the proportional gain K_p limits were investigated. They must be kept within these limits otherwise undesirable performance would be obtained. The system proved robustness in marinating a constant output voltage a part from any load or speed variations.

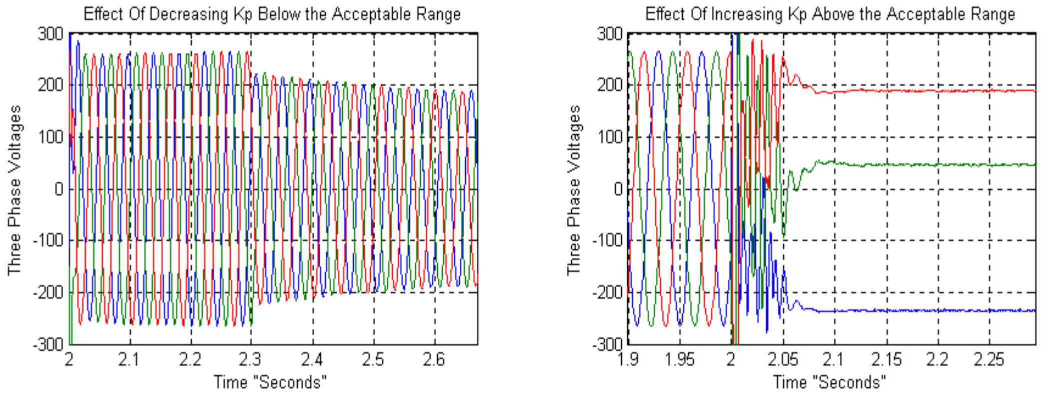

Fig. 5. Effect of the proportional gain, K_p, variation on the phase voltage.

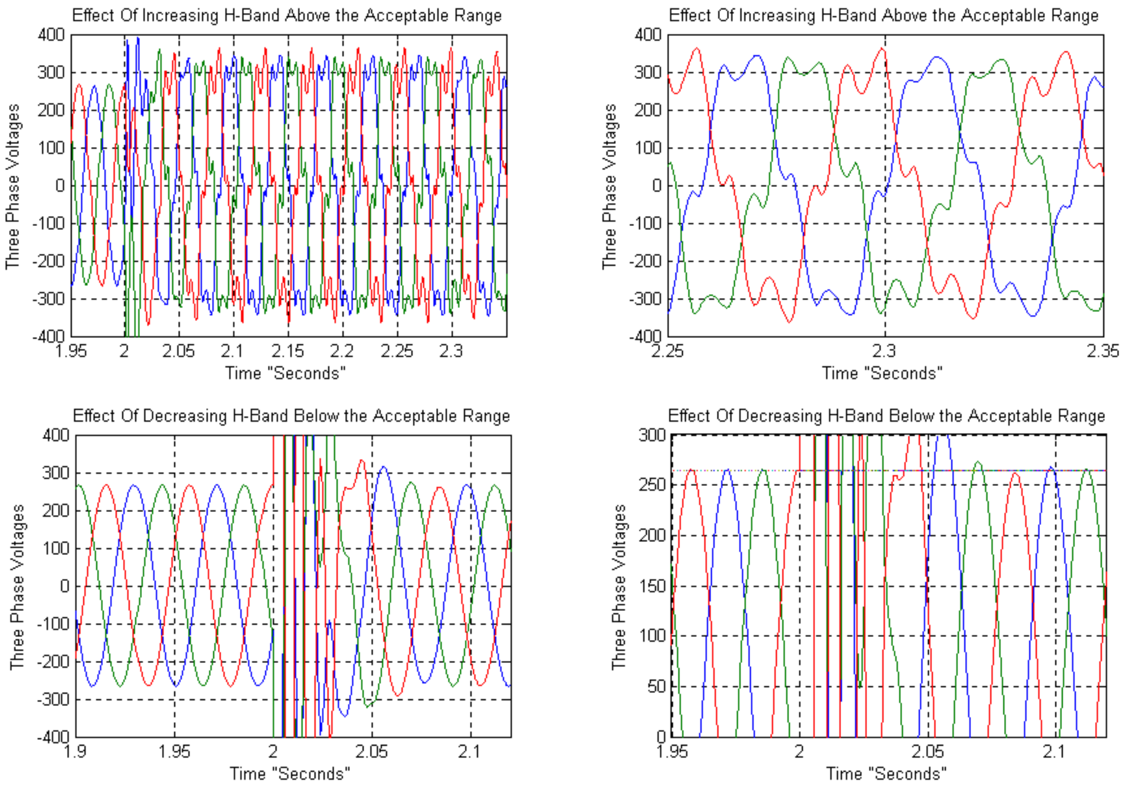

Fig. 6. Effect of hystersis band, ΔH, variation on the phase voltage.

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