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Robust and Efficient Control of Wind Conversion System based on a Squirrel Cage Induction Generator (SCIG)

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Abstract

This paper presents a control strategy for a squirrel cage Induction generator (SCIG)-based wind energy conversion system. Control strategies of the AC/DC converter is presented along with the mathematical modeling of the employed configuration. The maximum power point extraction of the wind turbine is addressed along with the proposed strategy. The backstepping approach is introduced to control the generator speed and regulate the flux. The wind system is then simulated in MATLAB-SIMULINK and the developed model is used to illustrate the behavior of the system. The simulation results are presented and discussed at the end of this paper.

Keywords: *Squirrel cage Induction generator (SCIG), backstepping control, wind energy conversion system, AC/DC converter, maximum power point extraction*

1. Introduction

The growing need for electrical energy and the will to preserve the nature justifies the use of renewable energy sources**.** The use of renewable sources for electric power generation has been a huge increase since the past decade. Increased economical and ecological woes have driven researchers to discover newer and better means of generating electrical energy. In this race, the production of electricity by wind turbine is actually the best method in comparison with the energy produced by the solar source conversion and this is due to the price per a kilo watt that is less elevated with respect to the second [1]. Among the most used and available technologies for wind turbines, the doubly fed induction generator (DFIG) is the most accepted because it presents greater benefits for a reduced conversion structure and efficient energy capture due to variable speed operation [2].

Different types of electric generators are used for the generation of electric energy from wind. These include the squirrel cage induction generators (SCIG), the doubly fed induction generator (DFIG) and the synchronous generator (SG) [3].

The squirrel cage induction generator (SCIG) is suitable for alternative energy source applications because it is cheap, has simple construction, good power/weight ratio, low maintenance levels, and it is robust and easily replaceable. For these reasons, the (SCIG) is being strongly considered as a good option in conjunction with the variable speed wind turbines [4].

Variable-speed wind turbines are advantageous for their potential capability of extracting more energy from wind resources. Thus, an MPPT control strategy is necessary to adjust the turbine rotor speed according to the variation of wind speeds so that the tip speed ratio can be maintained at its optimal value [5].

Several MPPT control algorithms have been proposed in the technical literature. The search control such as perturb and observe (P&O), anemometer-based method, and the fuzzy-logic based algorithms are easily implemented and are independent of wind turbine characteristics. In the P&O algorithm, the turbine speed is varied in small steps and the

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corresponding change in power is observed. Step changes are effected in a direction so as to move toward MPP. This process is continued until MPP is reached. By using this algorithm, maximum power corresponding to any wind velocity can be captured. But the time taken to reach MPP is long and a considerable amount of power loss takes place during the tracking phase. The anemometer-based MPPT algorithm, the wind velocity is measured and a reference speed for the induction generator (SCIG) corresponding to the MPP of the present wind velocity is set. Although this is a fast MPPT scheme, the overall cost of the system increases because anemometer is expensive. Fuzzy-control-based scheme is good, but is complex to implement. Neural networks could be an alternative approach for the MPPT control, but the requirement for offline training in order to learn the turbine characteristics might be a considerable drawback for several installations. An optimal torque controller that follows a quadratic relation between turbine torque and speed can provide faster dynamic response, however, it needs a priori knowledge of the turbine characteristics [6].

Several controller strategies have been used in the literature, citing the PID that is generally suitable for linear systems, the sliding mode for which the chattering problem, and fuzzy logic adapted to systems without a mathematical model [7].

In this work, the problem of controlling AC/DC converter is approached using the backstepping technique. While feedback linearization methods require precise models and often cancel some useful non linearity, backstepping designs offer a choice of design tools for accommodation of uncertain nonlinearities and can avoid wasteful cancellations.

The backstepping approach is applied to a specific class of switched power converters, namely ac-to-dc converters. In the case where the converter model is fully known the backstepping nonlinear controller is shown to achieve the control objectives i.e. speed and flux control of (SCIG) with respect to wind change. The desired speed is designed online using a an estimate of the speed reference corresponding to operation at maximum power generator wind power. The proposed strategy ensures that the MPP is determined, the generator speed is controlled to its reference value and the close loop system will be asymptotically stable. The stability of the control algorithm is analysed by Lyapunov approach [8].

The block diagram of a typical wind energy conversion system is shown in Figure 1. The transfer of the power produced by wind power system is made by AC/DC converter. that operates as a rectifier [8].

This paper is structured as follows. Section II presents the modeling of the SCIG system. The detailed control strategy is discussed in Section III. Section IV presents and discusses simulation and results followed by conclusions in Section V.

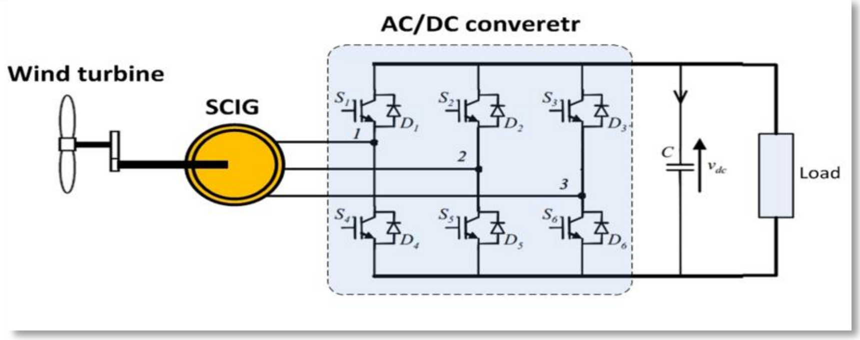


Fig 1 : SCIG-based Wind energy conversion system

2. Wind Energy Conversion System Modeling

The wind turbine modeling is inspired from [9]. In the following, the wind turbine components models are briefly described.

2.1. The Turbine Model

The aerodynamic power *P* captured by the wind turbine is given by

$$P = \frac{1}{2}\pi\rho R^2 Cp(\lambda)v^3 \qquad (1)$$

Where the tip speed ratio λ is given by:

$$\lambda = \frac{R\omega}{v} \qquad (2)$$

Where v is the wind, ρ is the air density, R is the rotor radius, C_p is the power coefficient and λ is the ratio of turbine blades tip speed to wind speed. Figure 2 illustrate generator power as a function of speed for differents wind speeds.

The rotor power (aerodynamic power) is also defined by

$$P_m = T_m \,.\, \omega_m \qquad (3)$$

where P_m and T_m are the mechanical power and the aerodynamic torque respectively. ω_m is the wind turbine rotor speed.

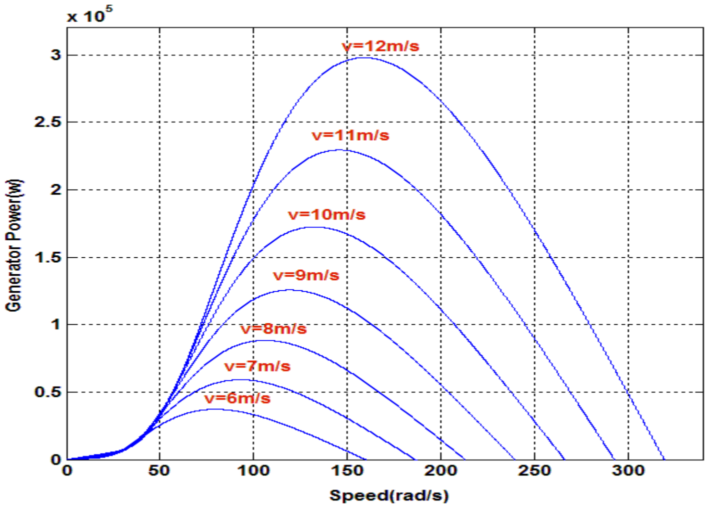


Figure 2. Generator Power as a Function of Speed for Differents Wind Speeds

The following simplified model is adopted for the turbine

$$J\frac{d\omega_m}{dt} = T_m - T_{em} - K.\omega_m \qquad (4)$$

where T_{em} is the generator electromagnetic torque, J is the turbine total inertia, and K is the turbine total external damping.

2.2. The SCIG Model

The control system is usually defined in the synchronous *d-q* frame fixed to either the stator voltage or the stator flux.

The voltages of the windings of the stator and the rotor according to the d-q axes are given by the following relations [5]

$$\begin{cases} v_{sd} = R_s\, i_{sd} + \frac{d\Phi_{sd}}{dt} - \omega_s . i_{sq} \\ v_{sq} = R_s\, i_{sq} + \frac{d\Phi_{sq}}{dt} + \omega_s . i_{sd} \\ v_{rd} = 0 = R_r\, i_{rd} + \frac{d\Phi_{rd}}{dt} - \omega_r . i_{rq} \\ v_{rq} = 0 = R_r\, i_{rq} + \frac{d\Phi_{rq}}{dt} + \omega_r . i_{rd} \end{cases} \qquad (5)$$

The electromagnetic torque is given by the following relation

$$T_{em} = \frac{P\,.\,M}{L_s}\left(\Phi_{sq} . i_{rd} - \Phi_{sd} . i_{rq}\right) \qquad (6)$$

The magnetic flux created by the windings of the stator and the rotor are given by the following relations

$$\begin{cases} \Phi_{sd} = L_s\, I_{sd} + m . L_m . I_{rd} \\ \Phi_{sq} = L_s\, I_{sq} + m . L_m . I_{rq} \\ \Phi_{rd} = L_r\, I_{rd} + m . L_m . I_{sd} \\ \Phi_{rq} = L_r\, I_{rq} + m . L_m . I_{sq} \end{cases} \qquad (7)$$

where *v* is the voltage, *i* the current, Φ is the flux, *R* is the resistance, *L* is inductance, *M* is the mutual inductance, T_{em} is the electromagnetic torque, and *P* is the pole pair number. L_m and *m* ($M=m.L_m$) are magnetizing inductance and turns ratio of the stator current and rotor current respectively.

The active and reactive stator powers are expressed by

$$\begin{cases} P_s = V_{sd} I_{sd} + V_{sq} I_{sq} \\ Q_s = V_{sq} I_{sd} - V_{sd} I_{sq} \end{cases} \qquad (8)$$

The above model (5) to (7) can be presented as differential equations for the stator currents and rotor flux vector components under the following form:

$$\begin{cases} \dot{x}_1 = a_1(x_2 . x_3 - x_7 . x_4) - a_2 . x_1 - a_3 . x_8 \\ \dot{x}_2 = -a_4 . x_2 - a_5 . x_4 + a_5 . x_7 - a_7 . x_1 . x_3 + a_8 . x_6 \\ \dot{x}_3 = a_9 . x_4 - a_{10} . x_3 + a_5 . x_7 - a_{11} . x_1 . x_7 \\ \dot{x}_4 = -a_4 . x_4 + a_5 . x_2 + a_6 . x_3 + a_7 . x_1 . x_7 + a_8 . x_5 \end{cases} \qquad (9)$$

Where:

$$a_1 = \frac{P.M}{J.L_r}\ ; \qquad a_2 = \frac{f}{J}\ ; \qquad a_3 = \frac{1}{J}\ ;$$

$$a_4 = \frac{{L_r}^2.R_s + {L_m}^2.R_r}{\sigma.L_s.{L_r}^2}\ ;\ a_5 = 1;\ a_6 = \frac{R_r.M}{\sigma.L_s.{L_r}^2}$$

$$a_7 = \frac{R_r.P}{\sigma.L_s.L_r} \;\; ; \;\; a_8 = \frac{1}{\sigma.L_s} \;\; ; \;\; a_9 = \frac{R_r.M}{L_r} \; ;$$

$$a_{10} = \frac{R_r}{L_r} \;\; ; \;\; a_{11} = P$$

and

$x_1 = \omega_m \; ; \; x_2 = i_{sq} \; ; \; x_3 = \phi_{rd} \; ; \; x_4 = i_{sd} \; ;$
$x_5 = v_{sd} \; ; \; x_6 = v_{sq} \; ; \; x_7 = \phi_{rq} \; ; \; x_8 = T_m \; ;$

Controls the electromagnetic torque and rotor direct flux will be obtained by controlling the dq-axes stator currents of the SCIG.

By choosing the two-phase dq related to rotating rotor field, and placing the rotor flux vector on the d-axis, we have $\phi_{rd} = \phi_{rd} = \phi_r$ and $\phi_{rq} = 0$. In this case, the model (9) becomes:

$$\begin{cases} \dot{x}_1 = a_1.x_2.x_3 - a_2.x_1 - a_3.x_8 \\ \dot{x}_2 = -a_4.x_2 - a_5.x_4 - a_7.x_1.x_3 + a_8.x_6 \\ \dot{x}_3 = a_9.x_4 - a_{10}.x_3 \\ \dot{x}_4 = -a_4.x_4 + a_5.x_2 + a_6.x_3 + a_8.x_5 \end{cases} \qquad (10)$$

3. Control Strategy

The architecture of the controller is shown in Figure 3. It is based on the three-phase model of the electromechanical conversion chain of the wind system [6].

The control strategy has an objective to extract maximum wind power by controlling the electromagnetic torque and d-axis flux of (SCIG).

3.1. MPPT Strategy

The control objective is to optimize the capture wind energy by tracking the optimal generator speed $\omega_m *$. The optimal speed which corresponds to operation at maximum power is approximated according to the wind speed:

$$\omega_m * = a_0 + a_1.v + a_2.v^2 \qquad (11)$$

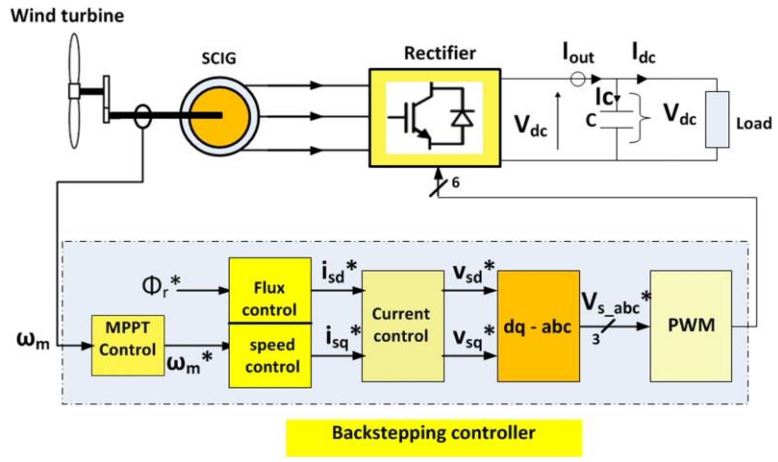


Figure 3. Control Strategy

The numerical values of a_0, a_1 and a_2 are deducted from the power curve. For each wind speed, there is the optimum speed corresponding to an operation of the maximum power to the system. To determine the value of a_0, a_1 and a_2, we must have three equations. Tooking three points of the power curve that we know the optimal wind speed as,
v = 12m / s then the optimal generator speed is w = 160 ras / s
v = 10m / s then the optimal generator speed is w = 130 rad / s
v = 8m / s then the optimal generator speed is w = 105rad / s
since we approximate the optimal speed to the formula
$w = a_0 + a_1 v + a_2 v^2$

There is three equations with three unknowns a_0, a_1 and a_2 :

$$\begin{bmatrix} 1 & 12 & 164 \\ 1 & 10 & 100 \\ 1 & 8 & 64 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} 160 \\ 130 \\ 105 \end{bmatrix}$$

By resolution of the three equations, we get

$$a_0 = 16;\ a_1 = 9.33;\ a_2 = 0.2222$$

3.2. Control of the AC/DC Converter

In order to extracting maximum power from turbine, mechanical speed and rotor flux, two state variables have been proposed for describing the (SCIG) model as follows:

$$\dot{x}_1 = a_1(x_2.x_3 - x_7.x_4) - a_2.x_1 - a_3.x_8 \qquad (12)$$
$$\dot{x}_3 = a_9.x_4 - a_{10}.x_3 + a_5.x_7 - a_{11}.x_1.x_7 \qquad (13)$$

Therfore, the errors are defined using the rotational speed and rotor flux:

$$e_1 = x_1 - x_1^* \qquad (14)$$
$$e_3 = x_3 - x_3^* \qquad (15)$$

In equations (12)-(13), x_2 and x_4 behaves as a virtual control input. Such an equation shows that one gets $\dot{e}_1=-k_1.e_1$ and $\dot{e}_3=-k_3.e_3$ ($k_1>0$; $k_3>0$ being a design parameters) provided that:

$$x_2 = (a_2.x_1 + a_3.x_8. - k_1 e_1)/a_1.x_3 \qquad (16)$$
$$x_4 = (a_{10}.x_3 - k_3 e_3)/a_9 \qquad (17)$$

As x_2 and x_4 are just a variables and not (an effective) control inputs, (12)-(13) cannot be enforced for all t≥0. Nevertheless, equation (18)-(19) shows that the desired value for the variable x_2 and x_4 are respectively:

$$x_2^* = (a_2.x_1 + a_3.x_8. - k_1 e_1)/a_1.x_3 \qquad (18)$$
$$x_4^* = (a_{10}.x_3 - k_3 e_3)/a_9 \qquad (19)$$

Indeed, if the errors:

$$e_2 = x_2 - x_2^* \qquad (20)$$
$$e_4 = x_4 - x_4^* \qquad (21)$$

The desired value x_2^* and x_2^* are called a stabilization function.

Deriving e_1 and e_3 with respect to time and accounting for (12)-(13)-(18) and (19), implies:

$$\dot{e}_1 = -k_1.e_1 + a_3.x_3.e_2 \qquad (22)$$
$$\dot{e}_3 = -k_3.e_3 + a_9.e_4 \qquad (23)$$

The Lyapunov function is defined as

$$V = \frac{e_1^2}{2} + \frac{e_2^2}{2} + \frac{e_3^2}{2} + \frac{e_4^2}{2} \qquad (24)$$

The time derivative of Lyapunov function V is given by

$$\dot{V} = e_1.\dot{e}_1 + e_2.\dot{e}_2 + e_3.\dot{e}_3 + e_4.\dot{e}_4 \qquad (25)$$

The time-derivative of the latter, along the (e_1, e_2,e_3,,e_4) trajectory is:

$$\dot{V} = -k_1.e_1^2 - k_2.e_2^2 - k_3.e_3^2 - k_4.e_4^2 \leq 0 \qquad (26)$$

Then, the control ($x_5^* = v_{sd}^*$, $x_6^* = x_{sq}^*$) laws are derived

$$x_5^* = (-a_9.e_3 + a_4.x_4 - k_4 e_4 - a_6.x_3 - a_5.\dot{x_2} + x_4^*)/a_8 \qquad (27)$$
$$x_6^* = (-a_3.e_1.x_3 + a_4.x_2 + a_5.x_4 - k_2 e_2 + a_7.x_1.x_3 + \dot{x}_2^*)/a_8 \qquad (28)$$

4. Simulation Results

The model of the (SCIG) based variable speed wind turbine system is built using MATLAB\SIMULINK. The parameters of the turbine and (SCIG) are given in the following Table:

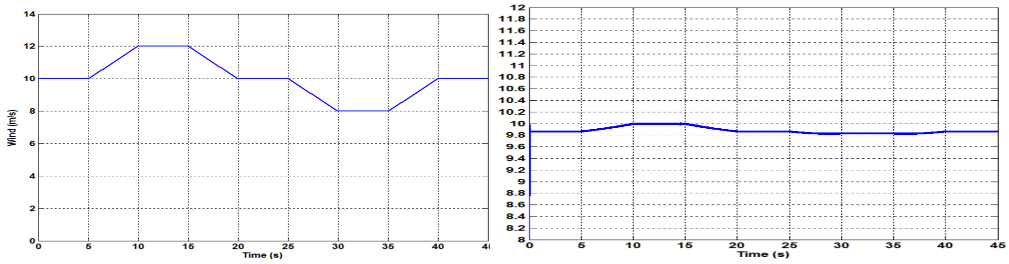
System	Parameter
Turbine	Jt =50 kg.m^2, Vt$_n$ =12m/s, R =14m
Multiplier	Mu = 46
SCIG	U$_s$= U$_r$ = 380V, P$_n$ = 300kw, ω$_n$=160 rad/s, f=50Hz, R$_r$ =46mΩ, R$_s$=63mΩ, M= 11.6mH, L$_s$ =11.8mH, L$_r$=11.8mH, P =2

Figure 4 shows the response of wind power system according to a velocity change. Figure 4.a shows the wind velocity profile imposed. Figure 4.b shows lambda. According to this figure, lambda is adjusted to its optimum value ($\text{Lambda}_{opt} = 10$).

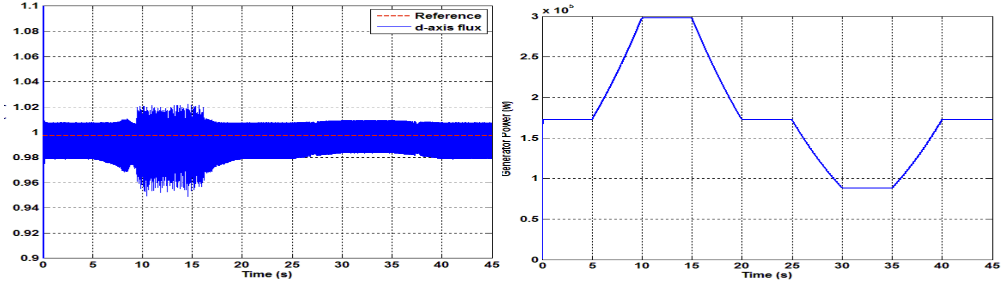
Figure 4.c shows the d-axis rotor flux. It's noted that the d-axis rotor flux is regulated to its reference value (ϕ_r=1wb).

Figure 4.d shows the mechanical power extracted from the wind power generator according to wind velocity change. According to the estimated power (Figure 2), the extracted wind power is maximum.

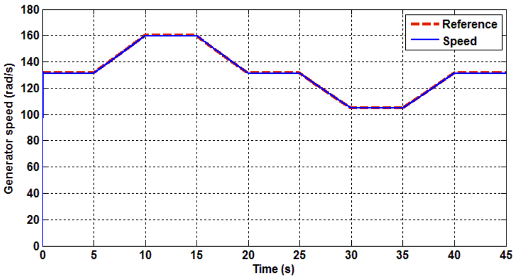
Figure 4.e shows the generator speed. The speed is regulated at the optimal value that corresponds to operation at maximum power. The reference of optimal speed is provided by the block called MPPT.



(a) Wind Velocity (b) Lambda



(c) Rotor Flux And Reference (d) Mechanical Power



(e) Generator Speed and Reference

Figure 4. Simulations Results

6. Conclusion

This paper has addressed the modeling and control of a wind system with variable speed based on a (SCIG) machine. We are interested in modeling of various components of wind system. To validate the power model and control approach of the wind system, we have performed a simulation in Matlab/Simulink. According to the simulation results, the backstepping control ensured with better efficiency the regulation of the rotational speed of the turbine which allows operation of the wind power system at maximum power and providing a decoupling between the control flux and speed.

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