Nonlinear Control of Variable wind Speed Conversion System Based on a Squirrel Cage Induction Generator (SCIG)

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Abstract: This study presents a control strategy for a Squirrel Cage Induction Generator (SCIG)-based wind energy conversion system. Control strategies of the AC/DC/AC 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 study.

Keyword: Squirrel Cage Induction Generator (SCIG), Grid Power, Unity Power Factor, Wind Energy Conversion System, Maximum Power Point Extraction

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 kilowatt that is less elevated with respect to the second (Suebkinorn and Neammanee, 2011). 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.

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) (Suebkinorn and Neammanee, 2011).

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 (Trapp et al., 2012).

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.

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 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 corresponding to the Maximum Power Point (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 (Mesemanolis and Mademlis, 2013).

In the grid-connected system, however, any amount of power generated by the wind energy based (SCIG) can be injected into the grid. Hence, at any wind velocity, the system can be operated at MPP to maximize the generation and utilization of power. The block diagram of a typical grid-connected wind energy conversion system is shown in Fig. 1. The transfer of the power produced by this system is made by two cascaded converters. The first is linked to the network operates as a rectifier and the second operates as an inverter is connected to the grid (Manaullah et al., 2012).

In this study, 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 nonlinearity, 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.

This study 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.

Wind Energy Conversion System Modeling

The wind turbine modeling is inspired from (Manaullah et al., 2012). In the following, the wind turbine components models are briefly described.

The Turbine Model

The aerodynamic power $P$ captured by the wind turbine is given by Equation 1:

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

where, the tip speed ratio $\lambda$ is given by Equation 2:

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

And $v$ is the wind, $\rho$ is the air density, $R$ is the rotor radius and $C_p$ is the power coefficient. $\lambda$ is the ratio of turbine blades tip speed to wind speed and $\beta$ is the turbine blades rotational speed. The Generator power as a function of generator speed for different velocity is illustrated in Fig. 2.

The rotor power (aerodynamic power) is also defined by Equation 3:

$$P = T_m \omega$$  (3)

where, $T_m$ is the aerodynamic torque and $\omega$ is the wind turbine rotor speed.

The following simplified model is adopted for the turbine Equation 4:

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

Where:

$T_{em} = $ The generator electromagnetic torque
$J = $ The turbine total inertia
$K = $ The turbine total external damping

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. For the proposed control strategy, the generator dynamic model written in a synchronously rotating frame $d$-$q$.

The voltages of the windings of the stator and the rotor according to the $d$-$q$ axes are given by the following relations (Kedjar and Al-Haddad, 2012):

$$
\begin{align*}
\frac{d}{dt} v_{sd} &= R_s i_{sd} + \frac{d}{dt} \Phi_{sd} - \omega_s i_{sq} \\
\frac{d}{dt} v_{sq} &= R_s i_{sq} + \frac{d}{dt} \Phi_{sq} + \omega_s i_{sd} \\
0 &= R_s i_{sd} + \frac{d}{dt} \Phi_{sd} - \omega_s i_{sq} \\
0 &= R_s i_{sq} + \frac{d}{dt} \Phi_{sq} + \omega_s i_{sd}
\end{align*}
$$

(5)
The magnetic flux created by the windings of the stator and the rotor are given by the following relations:

\[
\begin{align*}
\Phi_{sd} &= L_{sd} I_{sd} + m L_m I_{sd} \\
\Phi_{sq} &= L_{sq} I_{sq} + m L_m I_{sq} \\
\Phi_{rd} &= L_{rd} I_{rd} + m L_m I_{rd} \\
\Phi_{rq} &= L_{rq} I_{rq} + m L_m I_{rq}
\end{align*}
\]  

Where:

- \(v\) = The voltage
- \(i\) = The current
- \(\Phi\) = The flux
- \(R\) = The resistance
- \(L\) = Inductance
- \(M\) = The mutual inductance
- \(T_{em}\) = The electromagnetic torque
- \(P\) = The pole pair number
- \(L_m\) and \(m\) (?=mL_m) = Magnetizing inductance and turns ratio of the stator current and rotor current respectively

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:

\[
\begin{align*}
\dot{x}_1 &= a_1 (x_2 - x_3 - x_4 - x_5) - a_2 x_1 - a_3 x_6 \\
\dot{x}_2 &= -a_4 x_2 - a_5 x_3 + a_3 x_7 + a_1 x_8 \\
\dot{x}_3 &= a_6 x_6 - a_7 x_7 + a_8 x_6 \\
\dot{x}_4 &= a_4 x_4 + a_5 x_5 + a_1 x_7 + a_2 x_8 + a_3 x_9 + a_6 x_10
\end{align*}
\]  

Where:

\[
\begin{align*}
a_1 &= \frac{P M}{L_s v} & a_2 &= \frac{f}{J}; a_3 &= \frac{1}{T} \\
a_4 &= \frac{L_s L_r}{\sigma L_s L_r}^2; a_5 &= 1; a_6 &= \frac{R_s M}{L_r} \\
a_7 &= \frac{R_s P}{\sigma L_s L_r}; a_8 &= \frac{R_s M}{L_r}; \\
a_9 &= \frac{R_s}{L_r} a_{11} = P
\end{align*}
\]  

And:

\[
\begin{align*}
x_1 &= \omega_s x_2; x_2 &= i_3; x_3 = \phi_{sd}; x_4 = i_4; \\
x_5 &= v_{sd}; x_6 = v_{sq}; x_7 = \phi_{rd}; x_8 = T_n
\end{align*}
\]
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 Equation 8:

$$
\begin{align*}
\dot{x}_1 &= a_1 x_2 - a_1 x_4 - a_3 x_1 + a_6 x_6 \\
\dot{x}_2 &= a_6 x_1 - a_9 x_1 \\
\dot{x}_3 &= a_9 x_4 - a_{10} x_5 \\
\dot{x}_4 &= a_4 x_4 + a_4 x_2 + a_4 x_1 + a_4 x_5
\end{align*}
$$

Modeling Three-Phase Inverter

In this section, we focus on the modeling of the DC/AC inverter connected to power grid via the RL filter as illustrated in Fig. 4. The model of the three-phase grid connected DC/AC converter is presented by the following Equation 9 (Mehdi et al., 2013):

$$
\begin{align*}
\frac{d v_i}{dt} &= v_i + R_i i_i + L_i \frac{di_i}{dt} \\
\frac{d v_2}{dt} &= v_2 + R_2 i_2 + L_2 \frac{di_2}{dt} \\
\frac{d v_3}{dt} &= v_3 + R_3 i_3 + L_3 \frac{di_3}{dt}
\end{align*}
$$

The dynamic of the DC bus voltage is given by the following Equation 10:

$$
\frac{d V_s}{dt} = I_{dc} - I_{out}
$$

Control Strategy

The architecture of the controller is shown in Fig. 4. It is based on the three-phase model of the electromechanical conversion chain of the wind system (Mehdi et al., 2013).

The control strategy has three objectives:

- Control of AC/DC converter to extract maximum wind power by controlling the electromagnetic torque and d-axis flux of rotor SCIG
- Control of the DC/AC by controlling the DC bus voltage, active and reactive power Injected to electrical network

MPPT Strategy

The control objective is to optimize the capture wind energy by tracking the optimal generator speed $\omega_m^\ast$.

The optimum speed which corresponds to operation at maximum power is approximated according to the wind speed Equation 11:

$$
\omega_m^\ast = a_0 + a_1 \omega + a_2 \omega^2
$$

With:

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

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:

$$
\begin{align*}
\dot{x}_1 &= a_1 (x_2 - x_3 - x_4) - a_2 x_1 + a_3 x_5 \\
\dot{x}_3 &= a_4 x_4 - a_5 x_3 + a_6 x_1 - a_8 x_3 x_1
\end{align*}
$$

Therefore, the errors are defined using the rotational speed and rotor flux Equation 14 and 15:

$$
\begin{align*}
\dot{e}_1 &= x_1 - x_1^* \\
\dot{e}_3 &= x_3 - x_3^*
\end{align*}
$$

In Equation 12 and 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 Equation 16 and 17:

$$
\begin{align*}
x^* &= (a_2 - a_3 x_1 - a_5 x_3) / a_6 \\
x^* &= (a_4 - a_5 - a_6 x_3) / a_6
\end{align*}
$$

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

$$
\begin{align*}
x^* &= (a_2 x_1 + a_3 x_4 - k e_1) / a_6 \\
x^* &= (a_4 x_3 - k e_3) / a_6
\end{align*}
$$

Indeed, if the errors Equation 20 and 21:

$$
\begin{align*}
e_1 &= x_1 - x_1^* \\
e_3 &= x_3 - x_3^*
\end{align*}
$$
The desired value $x_1^*$ 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 Equation 22 and 23:

$$
\dot{e}_1 = -k_1 e_1 + a_1 x_1 e_2
$$

(22)

$$
\dot{e}_i = -k_1 e_i + a_1 e_4
$$

(23)

The Lyapunov function is defined as Equation 24:

$$
V = \frac{e_1^2}{2} + \frac{e_2^2}{2} + \frac{e_3^2}{2} + \frac{e_4^2}{2}
$$

(24)

The time derivative of Lyapunov function $V$ is given by Equation 25:

$$
\dot{V} = e_1 \dot{e}_1 + e_2 \dot{e}_2 + e_3 \dot{e}_3 + e_4 \dot{e}_4
$$

(25)

The time-derivative of the latter, along the $(e_1, e_2, e_3, e_4)$ trajectory is Equation 26:

$$
\dot{V} = -k_1 e_1^2 - k_1 e_2^2 - k_1 e_3^2 - k_4 e_4^2 \leq 0
$$

(26)

Then, the control $(x'_1 = v'_1, x'_2 = x'_4)$ laws are derived Equation 27 and 28:

$$
x'_1 = (a_4 e_1 + a_1 x_1 + k_1 e_2 + a_1 x_3 + x'_1) / a_4
$$

(27)

$$
x'_4 = (-a_4 e_1 + a_1 x_4 - k_1 e_3 + a_1 x_5 + x'_4) / a_4
$$

(28)

**DC/AC Control Strategy**

The three-phase grid connected inverter is controlled to:
• Regulating the dc bus voltage
• Provide a power factor close to unity (network current in phase with the network voltage)

Applying $dq$ transformation and developing the equations system (9), it is possible to find the differential Equation 29:

$$\begin{align*}
v_d &= R_i d_i + L_i \frac{di}{dt} + L_g \omega i_q + v_{g_d} \\
v_q &= R_i d_q + L_i \frac{di}{dt} + L_g \omega i_d + v_{g_q}
\end{align*}$$

(29)

where, $(v_{g_d}, v_{g_q})$ are the direct and quadrature components of the grid voltage respectively. $(i_d, i_q)$ are the direct and quadrature components of the grid current.

The term $\omega L_i i_q + v_{g_d}$ and $-\omega L_i i_d + v_{g_q}$ are compensated by a feed-forward action. By applying the Laplace transform to the compensated system, the transfer function of the inverter is given as Equation 30:

$$G_i(p) = \frac{v_d}{i_d} = \frac{v_q}{i_q} = \frac{1}{L_c p + R_g}$$

(30)

where, $v_d$ and $v_q$ are the inputs inverter voltages and the $i_d$ and $i_q$ are the outputs currents respectively.

The DC bus dynamics is given as Equation 31:

$$c \dot{V}_{dc} = i_{rec} - i_{load}$$

(31)

The application of the Laplace transform to (24) result in Equation 32:

$$c \cdot p \dot{V}_{dc} = i_{rec} - i_{load}$$

(32)

The term $i_{rec}$ is a disturbance in the control. It is assumed in this study that the DC bus loop is sufficiently fast, as to eliminate the perturbation term. For this reason, the DC bus function will be Equation 33:

$$G_{dc}(p) = \frac{V_{dc}}{i_{load}} = \frac{1}{c \cdot p}$$

(33)

The control loops of the inverter are shown in Fig. 5. Externally, there is the reactive power loop that controls the power factor and the loop to regulate the DC bus voltage. The current control loops use proportional-integral controllers. The controller gains are adjusted by the poles allocation method (Dinghui et al., 2009).

**Simulation Results**

The model of the wind turbine system based (SCIG) is built using MATLAB/SIMULINK. The parameters of the turbine and (SCIG) are given in the Table 1.

| System        | Parameter                      |
|---------------|--------------------------------|
| Turbine       | $J_t = 50 \text{ kg.m}^2$, $V_{t_i} = 12 \text{ m/s}, R = 14 \text{ m}$ |
| Multiplier    | $\mu = 46$                     |
| SCIG          | $U_s = U_r = 575 \text{ V}, P_n = 300 \text{ Kw}$, $\omega_n = 160 \text{ rad/s}, f = 50 \text{ Hz}$, $R_g = 46 \text{ m}\Omega, R_s = 63 \text{ m}\Omega$, $M = 11.6 \text{ mH}, L_s = 11.8 \text{ mH}, L_r = 11.8 \text{ mH}, P = 2$ |
| DC BUS        | $C = 20 \text{ mF}, V_{dc} = 1000 \text{ V}$ |
| RL Filter     | $R_g = 0.1 \text{ } \Omega, L_s = 0.6 \text{ mH}$ |
| GRID          | $U_g = 575 \text{ V}, f = 50 \text{ Hz}$ |

Table 1. Parameters of the turbine and (SCIG)

Fig. 5. Control strategy of the grid connected DC/AC converter
Figure 6 shows the response system for a wind change velocity. Figure 6a shows the wind velocity profile imposed. Figure 6b shows the power coefficient Cp. According to this figure, the power coefficient Cp is adjusted to its optimum value (Cp = 0.5).

Figure 6c shows the d-axis rotor flux. We note that the d-axis rotor flux is regulated to its reference value ($\phi_r = 1 \text{ wb}$).

Figure 6d shows the mechanical power extracted from the wind power generator. According to Fig. 3, the extracted power is maximum.

Figure 6e shows the speed of the SCIG machine. We note that the speed is regulated at the reference estimated by the MPPT.

Figure 6f shows the DC bus voltage. The reference of the DC bus voltage denoted $V_{dc,*}$ is set at 1000 V. According to this figure, the DC bus voltage is regulated to its reference.

Figure 6g shows the reactive power injected to the grid. The reference value of reactive power $Q_g*$ is set to 0 VAr, which guarantees a power factor close to unity. The reactive power of stator $Q_s$ is regulated to reference value.

**Conclusion**

This study has addressed the modeling and control of a wind system with variable speed of the wind based on a SCIG. We are interested in modeling of various components of wind system. In fact, the aerodynamic and mechanical models of the turbine have been developed. In order to establish different controllers of two converters, we have developed models of SCIG and liaison of the SCIG to the network via the inverter and RL filter.

To validate the modeling and control of the global wind system, we have performed a simulation for an operating point at variable wind speed.

According to the simulation results, the control strategy allowed regulation of the generator speed to the optimal value estimated by the MPPT algorithm. On the other hand a good decoupling between the adjustment of d-axis rotor flux and the generator speed. Finally, operating at a near-unity power factor at the injection of extracted wind power into the grid system.

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**Ethics**

This scientific research work is developed in the direction of improving the production energetic for a global population increasingly growing and also to respond to the global economic demand.

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