Optimal control based RST controller for Maximum Power Point Tracking of Wind Energy Conversion System

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Abstract— **This paper presents an LQ optimal control based RST controller for maximum power tracking in a wind energy conversion system (WECS) connected to the electrical grid through a back-to-back converter. Input-output discrete WECS model has been used to implement the input-output optimal control approach. The performance criterion has two terms: the first one is involved for maximum power tracking and the other one for the mechanical fatigue loading (control input) minimization. The obtained simulation results with the considered control and a variable wind profile show an adequate dynamic of the considered conversion system.**

Keywords—*Wind energy conversion system, Induction generator (IG), LQ optimal control, RST controller.*

I. INTRODUCTION

Wind energy is gaining popularity day by day and has become a viable solution for energy production, in addition to other renewable energy sources. The number of variable speed wind turbines is increasing comparing to fix ones [1]. The electrification of remote and rural areas is very important for the sustainable development of a country but provide power through grid extension is still very difficult and expensive.

Due to their advantages, the Variable-speed wind turbines are currently the most used wind energy conversion system especially the decoupling between the generating system and the grid frequency which makes them more flexible in terms of control and optimal operation [2].

At present, Induction generators are widely used in wind energy conversion systems (WECS) and Self-excited induction generator (SEIG) has become very popular for generating power from renewable energy sources, such as wind. SEIGs are an attractive alternative for the generation of electrical energy in remote locations where an electrical grid is not available especially that such systems are robust and low cost type of electrical machines. It is the most cost effective machine for applications in the medium voltage (MV) and low voltage (LV) distribution network (DN). This is due to its merits such as low cost, simple construction, low maintenance requirements and inherent overload capability [3].

The self-excited induction generator (SEIG) is considered as a good candidates for wind electricity generation in remote areas, because they do not need an external power supply to produce the excitation magnetic field but their main disadvantage, difficulty and limitation is poor voltage regulation, related with the instability of the generated voltage and frequency with the perturbations and variation in load and wind speed, such as, disconnection/reconnection to the grid or when it operates in an islanding mode. To overcome this issue different control strategies have been adopted by different searches which are oriented more towards the application of modern control.

The capability of the squirrel-cage induction generator has allowed its application in stand-alone power generating systems since it is discovered, in which the reactive power from the grid is not available and which are usually associated with renewable energy sources [4].

Self-excited induction generators (SEIG) are preferred because they are mechanically simple, have high efficiency and low maintenance cost [5]. Many research have studied to improve the use of SEIG in grid connected WECS. Vector control algorithms are often dominantly used for control of the self-excited induction generators (SEIGs) due to their superior control features. Most of them employ the classical PI controllers due to its simple design and satisfactory performance. More advanced approaches based on fuzzy logic and artificial intelligence have also been considered.

This paper focuses on mixed optimization criteria and introduces the optimal control structure in the form of an R-S-T controller of the wind energy systems in order to extract the maximum power from the wind.

The remaining part of this paper is organized as follows: The detail of system modeling is given in Section 2, followed by the details of LQ optimal control structure in the form of an R-S-T controller in Section 3. The test system details and simulation results are given in Section 4, and conclusion in Section 5.

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II. WIND ENERGY CONVERSION SYSTEM MODEL

The considered wind energy conversion system comprises a wind turbine, self-excited induction generator, a power electronic converter and the proposed control system connected to the grid. The wind turbine is connected to the electrical generator through a coupling device gear train. A proper controller is employed to avoid the disturbances and to protect the system or network [6]. Figure.1 shows the complete block diagram of the studied wind energy conversion system (WECS).

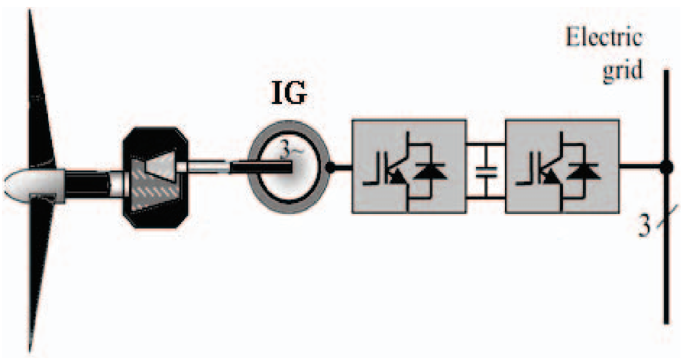

Fig.1. WECS based on an induction generator

II.1 WIND TURBINE MODEL

The captured mechanical power P_m from the wind is given by the following expression [7]:

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda,\beta) \quad (1)$$

Where:

R: is the blade radius of the wind turbine;
ρ : is the air mass density;
v : is the wind speed;
λ : is the tip speed ratio;
β : is the pitch angle;
C_p : is the wind turbine energy coefficient;

The tip speed ratio is defined as:

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

and w_r is the wind turbine rotor speed.

Several numerical approximations exist for $C_p(\lambda,\beta)$. The used relation is given by [8]:

$$C_p(\lambda,\beta) = (0.5 - 0.0167(\beta-2))\sin\left[\frac{\pi(\lambda+0.1)}{18-0.3(\beta-2)}\right] - 0.00184(\lambda-3)(\beta-2) \quad (3)$$

The $C_p - \lambda$ characteristics, for different values of the pitch angle β , are illustrated in Figure 2. The value of the power coefficient C_p is a function of λ and β , it reaches the maximum at the particular λ named λ_{opt}. Hence, a variable-speed wind turbine follows the $C_{P\max}$ to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at λ_{opt} .

The rotor power is defined by:

$$P = w_r T_a \quad (4)$$

Moreover

$$C_q(\lambda) = \frac{C_p(\lambda)}{\lambda} \quad (5)$$

It, thus, follows that the torque is given by

$$T_a = \frac{1}{2}\pi\rho R^3 C_q(\lambda) v^2 \quad (6)$$

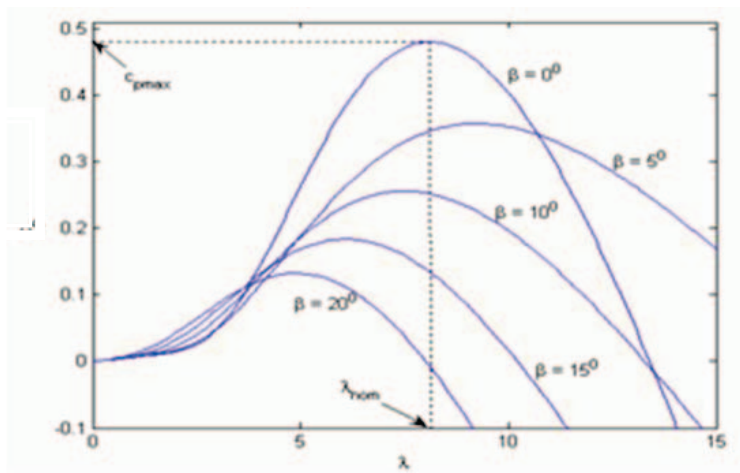

Fig. 2. $C_p(\lambda,\beta)$ Curve

II.2 INDUCTION GENERATOR MODEL

The model of the induction generator, expressed in d−q frame, is given by the following voltage system equations [9, 10]:

$$\begin{bmatrix} u_{ds} \\ u_{qs} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s + L_s p & -\omega_1 L_s & L_m p & -\omega_1 L_m \\ \omega_1 L_s & R_s + L_s p & \omega_1 L_m & L_m p \\ L_m p & 0 & R_r + L_r p & 0 \\ \omega_s L_m & 0 & \omega_s L_r & R_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (7)$$

The flux equations of stator are as follows:

$$\begin{bmatrix}\psi_{ds}\\ \psi_{qs}\\ \psi_{dr}\\ \psi_{qr}\end{bmatrix}=\begin{bmatrix}L_s & 0 & L_m & 0\\ 0 & L_s & 0 & L_m\\ L_m & 0 & L_r & 0\\ 0 & L_m & 0 & L_r\end{bmatrix}\begin{bmatrix}i_{ds}\\ i_{qs}\\ i_{dr}\\ i_{qr}\end{bmatrix} \tag{8}$$

The torque equations of vector controlling are as follows:

$$T_e = n_p \frac{L_m}{L_r} i_{sq}\psi_r \tag{9}$$

$$\psi_r = \frac{L_m}{T_r p + +1} i_{sd} \tag{10}$$

Where: ψ_r is the rotor flux, ω_1 the stator electricity angular velocity, ω_s is the slip angular velocity, L_s is stator inductance, L_r is the rotor inductance, L_m is the excitation circuit reactance. In the expression of components and rotor flux $T_r = L_r / R_r$.

III. THE PROPOSED CONTROL

To illustrate the performance of the LQ control for uncertain systems by avoiding undesirable effects, such as noise and the fast variation of the wind speed, an LQ optimal control approach is proposed based on R-S-T controller.

The corresponding input-output equation is [11]:

$$\Omega(i) = -\sum_{k=1}^{na} a_i \Omega(i-k) + \sum_{k=1}^{nb} b_j \Gamma_{em}(i-k-d) \tag{11}$$

Where: The rotational speed, the generator torque and the dead lag are respectively defined by: Ω, Γ_{em} and d.

The dead lag and the transfer function of the plant is:

$$H_p(q^{-1}) = q^{-d}\frac{B(q^{-1})}{A(q^{-1})} \tag{12}$$

Where q^{-1} is the one-sample-time delay operator, and

$$A(q^{-1}) = 1 + a_1 q^{-1} + \ldots + a_{na} q^{-na} \tag{13}$$

$$B(q^{-1}) = b_1 q^{-1} + \ldots + b_{nb} q^{-nb} \tag{14}$$

The performance criterion is expressed by the simplest expression as follow:

$$J = \left[\Omega^{opt}(i+1) - \Omega(i+1)\right]^2 + \alpha.\Delta\Gamma_{em}^2(i) \tag{15}$$

Where:

α: is a weighting parameter.

The first term represents the deviation of the controlled variable from its reference value Ω^{opt}, corresponding to the optimal regimes characteristic and the mechanical fatigue loading is given by the second the mechanical fatigue loading. The optimal control input results from the condition

$$\frac{\partial J}{\partial(\Delta\Gamma_{em})} = 0 \tag{16}$$

The reference Ω^{opt}(i +1) is considered as known; conversely, and in order to obtain the suitable prediction the variable Ω(i+1) must be replaced by a prediction $\hat{\Omega}(i+1)$. The plant model at equation (1) is rewritten [12]:

$$\begin{aligned}\Omega(i) &= \left[1 - A(q^{-1})\right]\Omega(i) + B(q^{-1})\Gamma_{em}(i)\\ &= z^{-1}A^*(q^{-1})\Omega(i) + q^{-1}\left[q^{-1}B^*(q^{-1}) + b_1\right]\Gamma_{em}(i)\end{aligned} \tag{17}$$

Where

$$\begin{cases} A^*(q^{-1}) = -a_1 - a_2 q^{-1} - \ldots - a_{na} q^{-na+1}\\ B^*(q^{-1}) = b_2 + b_3 q^{-1} + \ldots + b_{nb} q^{-nb+2}\end{cases} \tag{18}$$

The predictor equation that provides $\hat{\Omega}(i+1)$ is obtained by replacing the discrete time *i*, by *i+1*.

$$\hat{y}(i+1) = A^*(q^{-1})\Omega(i) + B^*(q^{-1})\Gamma_{em}(i-1) + b_1\Gamma_{em}(i) \tag{19}$$

The predicted value at Equation (9) is replaced in Equation (5); it results in

$$J = \begin{Bmatrix}\Omega^c(i+1) - \left[1 + A^*(q^{-1})\right]\Omega(i) + A^*(q^{-1})\Omega(i-1)\\ - B^*(q^{-1})\Delta\Gamma_{em}(i-1) - b_1\Delta\Gamma_{em}(i)\end{Bmatrix}^2 + \alpha.\Delta\Gamma_{em}^2(i) \tag{20}$$

By imposing the condition at Equation (6) the optimal control expression results as [13]:

$$\Delta\Gamma_{em}(i) = \eta\left\{\Omega^c(i+1) - \left[1 + A^*(q^{-1})\right]\Omega(i) + A^*(q^{-1})\Omega(i-1) - B^*(q^{-1})\Delta\Gamma_{em}(i-1)\right\} \tag{21}$$

Where:

$$\eta = \frac{b_1}{b_1^2 + \alpha} \tag{22}$$

Figure 3 illustrates the optimal control law, implemented as an R-S-T controller and the transfer functions is given by:

$$R(z^{-1}) = \eta\begin{bmatrix}1 + a_1 + (a_2 - a_1)z^{-1} + \ldots + (a_{na} - a_{na-1})z^{-na+1}\\ - a_{na} z^{-na}\end{bmatrix} \tag{23}$$

$$S(z^{-1}) = \left[1 + \eta(b_2 z^{-1} + b_3 z^{-2} + \ldots + b_{nb} z^{-nb+1})\right](1 - z^{-1}) \tag{24}$$

$$T(z^{-1}) = \eta \tag{25}$$

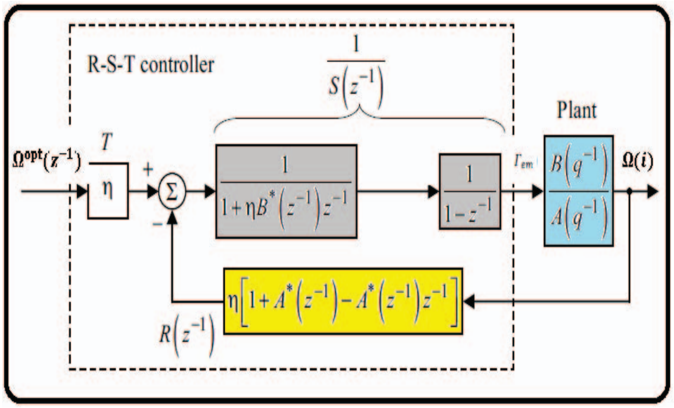

Fig. 3. LQ optimal control structure based on RST controller

The input-output discrete model has resulted from a statistic identification procedure of the torque reference and the corresponding speed response of the system. The obtained model is in following:

$$\begin{cases} A(q^{-1}) = 1 - 1.945.q^{-1} + 1.038.q^{-2} - 0.09.79.q^{-3} \\ B(q^{-1}) = 0.4224.q^{-1} - 0.7725.q^{-2} + 0.3522.q^{-3} \end{cases} \quad (26)$$

The transfer functions R (z^{-1}), S (z^{-1}) and T (z^{-1}) of the optimal controller have been computed by using Equations (13), (14) and (15), for α=8 :

$$\begin{cases} R(z^{-1}) = -0.1521 + 0.1541 \cdot z^{-1} - 0.0583 \cdot z^{-2} + 0.004689 \cdot z^{-3} \\ S(z^{-1}) = 1 - 1.04 \cdot z^{-1} + 0.05809 \cdot z^{-2} - 0.01819 \cdot z^{-3} \\ T(z^{-1}) = -0.0516 \end{cases} \quad (27)$$

IV. SIMULATION RESULTS AND INTERPRETATION

The robust LQ optimal control based on an R-S-T controller was numerically simulated in Matlab/SIMULINK. The aim of the robust controller structure is to maximize the energy captured from the wind. The used Induction generator and the wind turbine parameters are respectively shown in Tables 1 and 2. The adopted speed wind profile is represented in Figure. 4. The Power coefficient (C_p) and tip speed ratio (λ) evolutions are shown in Figs. 5 and 6 respectively. It can be seen that when the system is stable, C_p is stable down, it is located basically in 0.47, while tip speed ratio fluctuates around its optimal value 7. Figure.7 is the actual electromagnetic torque and its reference.

From Fig.7, it can be seen that the electromagnetic torque can follow its reference value quickly.

Table 1. *IG parameters*

Parameters	Values
The stator and rotor resistance	R_s=1.265 ,R_r=1.430
d,q inductances	L_d=0.1452mH , L_q=0.1452mH
Pole number	2

Table 2. *Parameters of wind turbine*

Parameters	Values
The air density	1.25
The blade radius	2.5
The maximum wind power conversion coefficient	0.47
The optimal tip speed ratio	7

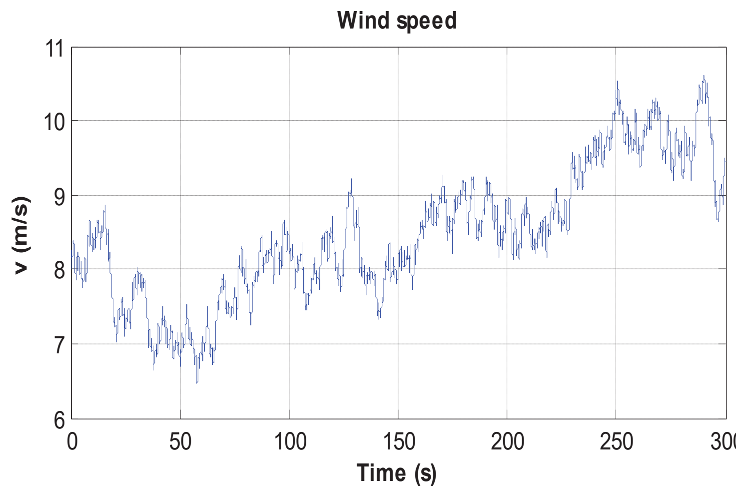

Fig.4. Wind speed

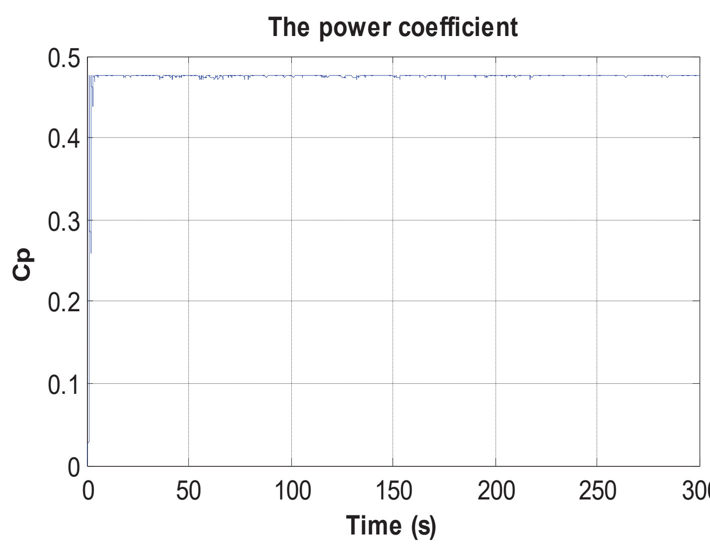

Fig.5. The power coefficient

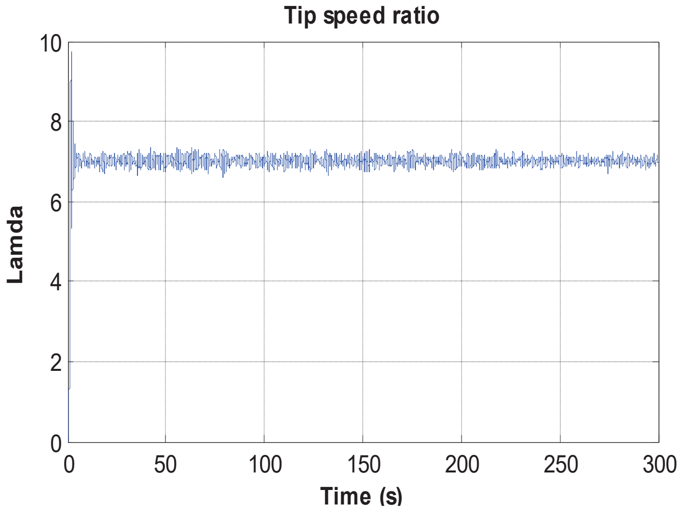

Fig.6. Tip speed ratio

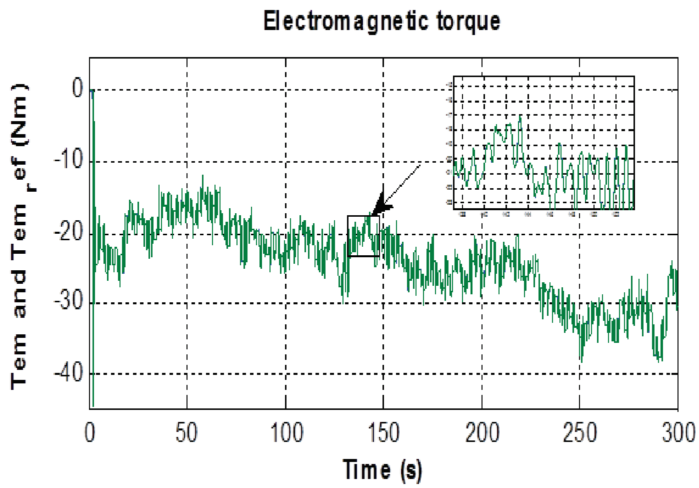

Fig.7. Actual electromagnetic torque

V. Conclusions

In this paper, the optimization of extracted power from a wind energy conversion system connected to the grid through a back-to-back converter is presented based on LQ optimal control structure using an R-S-T controller for the induction generator. The proposed control approach aims at minimizing a performance criterion having two contradictory elements: minimization of the distance from the optimal rotational speed and minimization of the control input (electromagnetic torque) variations. The balance between these parameters can be adjusted by means of a weighting parameter, α. The obtained results are useful and demonstrate that RST controller presents good performance and which can be successfully employed in wind energy application in order to ensure robustness and the quality of the produced energy.

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