Robust fractional control via feedback linearization strategy of a PMSG based wind energy conversion system.

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***Abstract*—This paper outlines the development of a feedback linearization control (FLC) scheme of permanent magnet synchronous generator (PMSG) based wind energy conversion system (WECS), which attempts to extract the maximum wind power by using a robust fractional theory. The FLC strategy can fully decouple and linearize the original nonlinear system and thus provide an optimal controller crossing a wide range operating conditions. It performs better than the traditional control techniques. The method is based on the feedback linearization technique and the Fractional control theory. A simulation study is carried out on a 3 kW WECS to show the effectiveness of the proposed control scheme.**

Keywords—WECS; PMSG; MPPT; Feedback Linearization Control ;Fractional Control.

I. INTRODUCTION

Rising demand for energy, diminishing fossil fuel sources and concerns about pollution levels in the environment are the main drivers of electricity generation based on renewable sources of energy [1]. Renewable energies, such as solar, wind, and tidal energy, are clean, inexhaustible and environmentally friendly. Because of all these factors, wind power generation has attracted a great deal of attention in recent years [2].The multiplication of wind turbines has led electrical engineers to conduct investigations in order to improve the efficiency of electromechanical conversion and the quality of the energy supplied [3].

Wind energy conversion systems (WECS) based permanent magnet synchronous generator (PMSG) are widely used in medium and high power wind turbines due to its robustness, its mechanical simplicity and except initial installation costs [4]. They are the object of particular attention because of their high efficiency. However, their analysis and control is a difficult task, because of nonlinearities and load torque. In order to overcome the difficulties associated with the design of a regulator for the PMSG, several control approaches have been proposed such as conventional PI control [5], fuzzy logic PI control [6], Adaptive control [7], neuronal control [8] , sliding mode control [9].

Recently, many design methods based on the principles of feedback linearization control have been proposed [10,11]. Actually, the popular linearization techniques can be basically categorized into three groups: standard form of linearization technique (SLT) using Taylor's series expansion, the direct feedback linearization (DFL), and the differential geometric linearization technique (DGT)[12-14].

Feedback linearization techniques are proposed to linearize highly nonlinear dynamic systems [15]. This involves a static state feedback and a special nonlinear coordinate change. The major disadvantage of these techniques is their direct dependence on the parameters of the installation. In recent years, thanks to developments in the theory of nonlinear control, researchers have developed several robust control laws. the combination of these robust laws with feedback linearization techniques has been an admirable success in the robustness of the control scheme. In the literature, these control designs can be found in many industrial applications. For example, Ref [16] has proposed An input/output feedback linearization method based sliding mode control strategy for the hydraulic generator regulating system (HGRS) with external disturbance and system uncertainties. Reference [17] has also proposed a feedback linearization controller based particle swarm optimization for maximum power point tracking of wind turbine equipped by PMSG connected to the grid.

Recently, fractional calculus based fractional order PID (FOPID) control found its way into complex mathematical and physical problems to achieve improved control performance over the traditional PID controller [18].

This work proposes a combination between robust fractional theory and feedback linerization control scheme for maximum wind power capture. The advantage of globally robust control consistency of nonlinear fractional robust control and superiority of structure simplicity of feedback linearisation control are beneficially incorporated by the proposed approach. The paper is organized as follows: section II is devoted to develop the model of the WECS while Section III designs the fractional theory based feedback linearization control of PMSG for MPPT. Section IV presents simulation results. Lastly, conclusions are summarized in Section V.

II. System Modeling

The block diagram of the PMSG based WECS which is connected to the power grid bus via back – to – back voltage source converter is shown in Figure.1

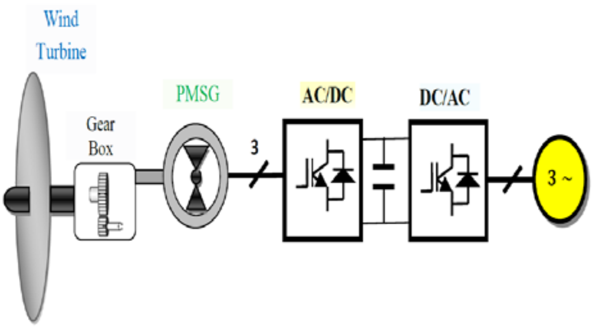

Fig. 1. The configuration of a PMSG – based WECS

A. Wind turbine model

The aerodynamic part transforms the kinetic energy of the wind into a mechanical energy and torque translated by the rotation of the rotor of the generator [19].

$$P_{wt} = \frac{1}{2}\pi\rho R^2 v^3 C_p(\lambda) \quad (1)$$

$$\Gamma_{wt} = \frac{1}{2}\pi\rho R^3 v^2 C_\Gamma(\lambda) \quad (2)$$

Where P_{wt} is the mechanical power, ρ is the air density, R is the blade radius of wind turbine, v is the wind speed, $C_p(\lambda)$ is the power coefficient, $C_\Gamma(\lambda)$ is the torque coefficient, and λ is the tip speed ratio given by:

$$\lambda = \frac{\Omega_l R}{v} \quad (3)$$

Where Ω_l is the low-speed shaft rotational speed. $C_p(\lambda)$ and $C_\Gamma(\lambda)$ are related by the following equation :

$$C_p(\lambda) = \lambda C_\Gamma(\lambda) \quad (4)$$

The theoretical upper limit of the power coefficient $C_{p-\max}$ is given by Betz's limit [20]:

$$C_{p-\max} = \frac{16}{27} \approx 0.59 \quad (5)$$

The reference torque resulting from the optimization block must answer two problems: the maximization of the power and the management of the operating zones of the wind turbine [21]. The ratio between the power extracted from the wind and the total power theoretically available has a maximum defined by the Betz limit. This limit is in fact never reached and each wind turbine is defined by its own power coefficient expressed as a function of the relative speed representing the ratio between the speed of the wind turbine and the wind speed. Figure.2 illustrates an example of power curves of a wind turbine .

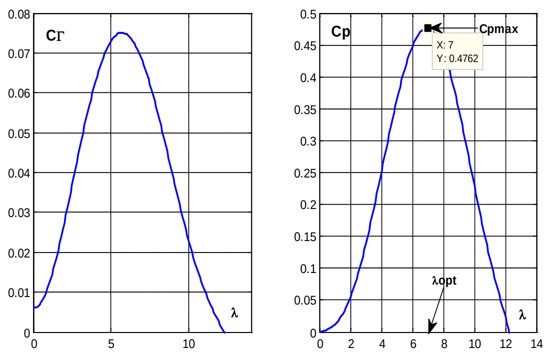

Fig. 2. Wind turbine power and torque coefficients.

B. Mechanical shaft system modelling

The dynamics of mechanical shaft system and mechanical torque of PMSG is given by [22]:

$$J_t \frac{d\Omega_h}{dt} = \Gamma_{wt} - \Gamma_{em} - F\Omega_h \quad (6)$$

Where Ω_h is the high-speed shaft rotational speed. J_t is the total inertia of the drive train which equals to the summation of wind turbine inertia constant and generator inertia constant, F is the viscous friction coefficient. In addition, active power is calculated as

$$P_a = \Gamma_{em}\Omega_h \quad (7)$$

With Γ_{em} being the electromagnetic torque.

C. PMSG model

The dynamics of PMSG in the d – q reference frames is written as [22]

$$\begin{cases} V_d = R_s i_d + L_d \dfrac{di_d}{dt} - \Phi_q \omega_s \\ V_q = R_s i_q + L_q \dfrac{di_q}{dt} + \Phi_d \omega_s \end{cases} \tag{8}$$

where R_s is the stator resistance, V_d , V_q are d and q stator voltages, L_d , L_q are d and q inductances and ω_s is the stator pulsation,

$$\Phi_d = L_d i_d + \Phi_m \tag{9}$$

$$\Phi_q = L_q i_q \tag{10}$$

are d and q fluxes and Φ_m is the flux that is constant due to permanent magnets. Thus, the model at Equation (8) becomes

$$\begin{cases} V_d = R_s i_d + L_d \dfrac{di_d}{dt} - L_q i_q \omega_s \\ V_q = R_s i_q + L_q \dfrac{di_q}{dt} + (L_d i_d + \Phi_m)\omega_s \end{cases} \tag{11}$$

The PMSG model with the equivalent circuit in the (d, q) reference can be expressed as

$$\begin{cases} \dfrac{d}{dt} i_d = -\dfrac{R_s + R_L}{L_d + L_L} i_d + \dfrac{p\left(L_q - L_L\right)}{L_d + L_L} i_q \Omega_h \\ \dfrac{d}{dt} i_q = -\dfrac{R_s + R_L}{L_q + L_L} i_q - \dfrac{p\left(L_d + L_L\right)}{L_q + L_L} i_d \Omega_h + \dfrac{p\Phi_m}{L_q + L_L} \Omega_h \end{cases} \tag{12}$$

The electromagnetic torque is obtained as

$$\Gamma_{em} = p\left[\Phi_m i_q + \left(L_d - L_q\right) i_d i_q\right] \tag{13}$$

Where p is the number of pole pairs, and R_L and L_L are respectively the equivalent chopper resistance and inductance.

III. ROBUST FRACTIONAL CONTROL BASED FEEDBACK LINEARIZATION TECHNIQUE

The idea of feedback linearization tchnique is to use a transformation, *z = T (x)*, and to apply a feedback control law, u, which transforms the nonlinear system into a linear system. Then, after obtaining a linear system, the usual linear control design methods can be applied for stabilization.

We consider a class of nonlinear systems of the form

$$\begin{cases} \dot{x} = f(\mathrm{x}) + \mathrm{g}(\mathrm{x})\,\mathrm{u} \\ y = h(x) \end{cases} \tag{14}$$

With:

$$f(x) = \begin{bmatrix} \dfrac{1}{L_d + L_L}\left(-R_s x_1 + p\left(L_q - L_L\right) x_2 x_3\right) \\ \dfrac{1}{L_q + L_L}\left(-R_s x_2 - p\left(L_d + L_L\right) x_1 x_3 + p\Phi_m x_3\right) \\ \dfrac{1}{J_t}\left(d_3 x_3^2 - p\Phi_m x_2\right) \end{bmatrix}$$

$$g(x) = \left[-\frac{1}{L_d + L_L} x_1, -\frac{1}{L_q + L_L} x_2, 0\right]^T$$

$h(x) = x_3$.

The state vector is defined as.

$x = \left[x_1, x_2, x_3\right]^T = \left[i_d, i_q, \Omega_h\right]^T, u = \left[u_1, u_2\right] = \left[R_L, v\right].$

The system given by Eq.(14) is considered as non-linear with smooth functions whose synthesis of feedback linearisation control is possible to make the system linear [15]. The nonlinear system equation (14) is said to be feedback linearizable if there exists a diffeomorphism $T : D \rightarrow R^n$ such that $D_z = T(\mathrm{D})$ contains the origin and the change of variables $z = T(x)$ transforms the system (14) into the form:

$$\dot{z} = Az + B\gamma(x)\left[u - \alpha(x)\right] \tag{15}$$

The advantage of the representation in (15) is the ability to choose a feedback control law that cancels out the nonlinearities of the system. The control objective can be achieved using the ideal control law

$$u^* = \frac{1}{\beta(x)}\left(-\alpha(x) + \upsilon\right) \tag{16}$$

Hence, we need to calculate the functions $\alpha(x)$ and $\beta(x)$. These functions are given by:

$$\begin{cases} \alpha(x) = L_f^2 h(x) \\ \beta(x) = L_g L_f h(x) \end{cases} \tag{17}$$

After computation using the WECS data, there is

$$\begin{cases} L_f^2 h(x) = -d_4 . f_2 + (d_2 v + 2d_3 x_3). f_3 \\ L_g L_f^{r-1} h(x) = -d_4 \, a_3 . x_2 \end{cases} \quad (18)$$

With

$$\begin{cases} d_1 = 1/2\pi\rho R^3 a_0 ; d_2 = 1/2\pi\rho R^4 a_1 ; d_3 = 1/2\pi\rho R^5 a_2 \\ a_0 = 0.1253; a_1 = -0.0047; a_2 = -0.0005 \end{cases}$$

And f_1 and f_2 being components of function f from Equation (14).The direct coordinates transform is [10]:

$$\begin{cases} z_1 = h(x) = \Omega_h \\ z_2 = d_1 v^2 + d_2 v\Omega_h + d_3 \Omega_h^2 - d_4 i_q \\ z_3 = a_3 \dfrac{i_d}{i_q} \end{cases} \quad (19)$$

And the inverse coordinates transform is

$$\begin{cases} i_d = a_3 z_3 \dfrac{d_1 v^2 + d_2 v z_1 + d_3 z_1^2 - z_2}{d_4} \\ i_q = \dfrac{d_1 v^2 + d_2 v z_1 + d_3 z_1^2 - z_2}{d_4} \\ \Omega_h = z_1 \end{cases} \quad (20)$$

The control input is calculated using pole placement technique and fractional theory:

$$u = -\begin{bmatrix} k_1 & k_2 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + k_I \varepsilon \quad (21)$$

With :

$$\varepsilon = \frac{1}{s^\mu}(y_{ref} - y) \quad (22)$$

Since the control of the wind energy conversion system aims at the extraction of the maximum wind power (MPPT) that will be obtained by the drive of the generator at a speed Ω_h which must continue asymptotically the optimal reference speed:

$$y_r(t) = \Omega_h^* = \frac{\lambda_{opt} . i . v(t)}{R} \quad (23)$$

With λ_{opt} being the optimal tip speed ratio.

The block diagram of the maximum power extraction using feedback linearization strategy and fractional control is presented in Figure.3.

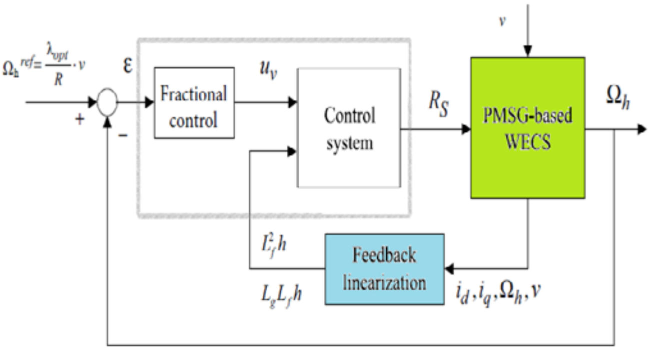

Fig. 3. Robust fractional control via feedback linearization strategy of a PMSG based WECS.

IV. Simulation Results

The simulation is carried out with Matlab/Simulink for a 3KW PMSG-based wind energy conversion system (Figure.1) with a maximum power coefficient $C_{p\text{-}max}$=0.47 which corresponds to an optimal tip speed ratio λ_{opt}=7.The simulation scheme is illustrated in Figure.3, whose parameters are given in Table.1.

Simulations were made with respect to the extraction of the MPPT maximum power for a time horizon of 3 min, using a pseudo-random wind speed sequence with an average turbulence intensity *I=0.17*, obtained using the Von Karman spectrum as shown in Figure.

The tracking test under wind fluctuations (Figure.4) whose extraction of the optimal power is guaranteed by the maintenance of both the power coefficient at its maximum value $C_{p-\max}$ (Figure.5) and TSR at its optimal value (Figure.6). This allows the generator to be rotated at its optimum speed (Figure.7 and 8).

According to Figure.9, it is easy to observe that the operating point distribution is given around the optimal regimes characteristic (ORC) in the speed-power plane. As a result, the figure confirms the effectiveness of the proposed controller in which the variance of the operating point around CRO is always satisfied.

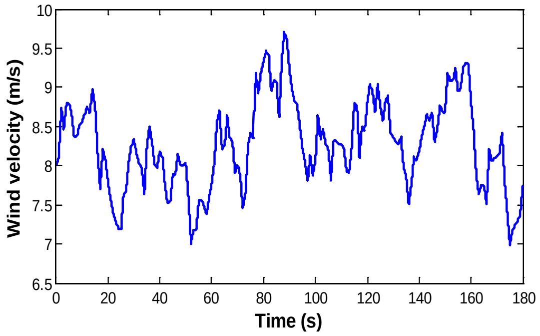

Fig. 4. Wind speed

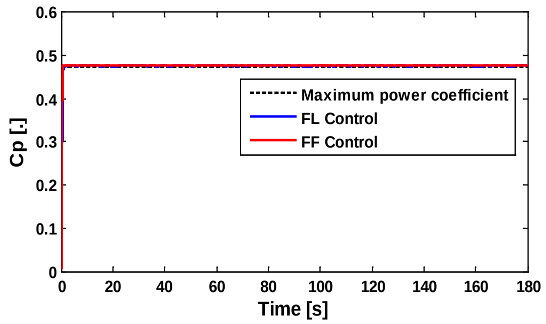

Fig. 5. Power coefficient

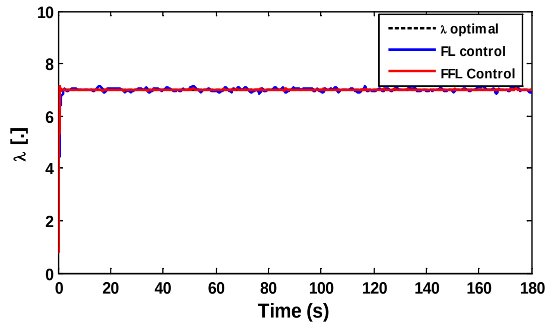

Fig. 6. Tip speed ratio

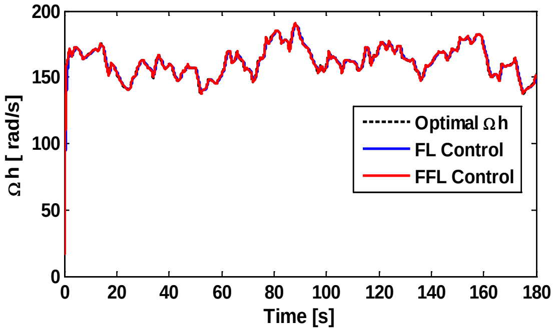

Fig. 7. Generator speed

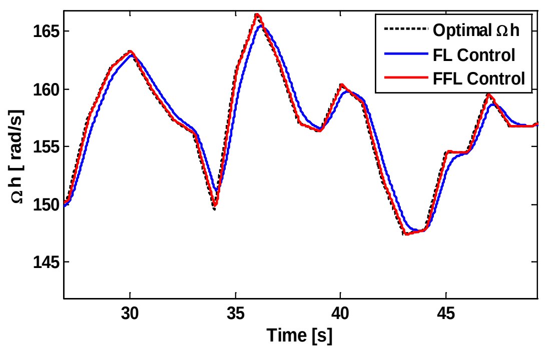

Fig. 8. Generator speed (+ zoom)

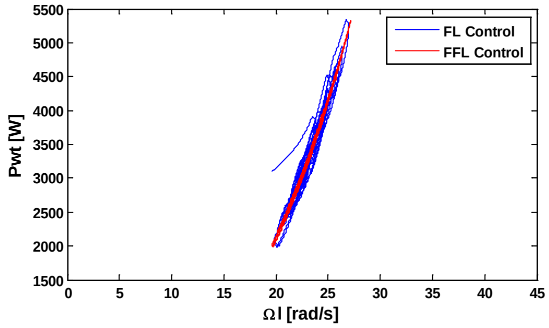

Fig. 9. Optimal power point tracking

TABLE I. PARAMETERS OF THE LOW-POWER (3-KW) RIGID-DRIVE-TRAIN PMSG-BASED WECS

Turbine rotor	Drive train	PMSG
Blade length: R=2.5 m.	*Multiplier ratio: i=7 Jh=0.5042 kg.m2 Efficiency : η=1*	*p=3, Rs=3.3 Ω, Φm=0.4382 Wb, Ld=41.56 mH, Lq=41.56 mH, Rln=80 Ω, Vs=380.*

V. CONCLUSIONS

In this paper, we have presented robust fractional control combined with feedback linearization strategy for maximum power point tracking of a wind conversion system equipped with permanent magnet synchronous generator .In order to ensure robustness against possible disturbances and to extract maximum power under stochastic wind conditions, a study of the nonlinear control of a wind energy conversion chain based on a permanent magnet synchronous generator autonomous operation is performed. The elaborate command addresses system nonlinearity issues as well as parametric uncertainty. It is based on the feedback linearization technique associated with a control law derived from the fractional theory. The results obtained showed the performance and efficiency of the proposed control technique.

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