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Enhancement of DFIG performance at high wind speed using fractional order PI controller in pitch compensation loop

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ABSTRACT

Doubly fed induction generator (DFIG) has been widely applied in wind farms. Meanwhile, DFIG control at high wind speeds has become an important issue. In this regard, the main task of pitch angle control loop is too important by the wind speed increase above the middle speeds (e. g. 12 m/s) to limit DFIG active power and rotor speed and to control the machine performance. In this study, a fractional order PI controller (FOPI) is designed and applied for the pitch angle compensation control loop to improve the DFIG performance at the high wind speed of 18 m/s. Due to using the fractional order coefficient as an extra control variable in the FOPI controller function in comparison with the PI controller, a preferable control scheme would be realized in the pitch angle control by the wind speed increase to high values. In this regard, the various simulation results for monitoring the active power and rotor speed are obtained in the multi machine test system including the DFIGs considering high wind speed operating mode via using MATLAB/SIMULINK software. In addition, different kinds of transient faults are considered to evaluate the performance of the proposed FOPI controller, instead of the conventional PI controller. The results validate the advantage of using the FOPI control scheme in the pitch angle control loop for promoting the DFIG active power and rotor speed profiles.

1. Introduction

High wind speed penetration in wind power plants causes problems such as over loading, instability, frequency changes and power quality disturbances [1–3]. By wind speed increase, pitch angle control process in variable speed wind turbines [4–10] has the main role to limit aerodynamic power produced by wind turbine via increasing blade pitch angles to protect generator against over loading. Although the modern pitch angle control based on the adaptive back stepping method using servo valve which is controlled by the hydraulic motor is introduced by the authors of [11]. Doubly fed induction generator (DFIG) [12,13] has widespread application in wind power plants due to high control abilities. Therefore, DFIG has been applied in hybrid PV-wind system with wind turbine generators [14]. The pitch angle control in DFIG has a significant task to reduce the destructive effects caused at high wind speed. The comprehensive pitch control scheme includes the DFIG rotor speed and active power control loops for extracting the rotor speed and active power deviations from their references. The deviations as the active power and rotor speed errors would be sent to the pitch actuator loop for deriving the pitch angle reference values (β_{ref}) [15–17]. By defining β_{ref}, the proper values of the pitch angle profile (β) would be extracted via the pitch servo control.

Fractional order PI controller (FOPI) [18] as a particular kind of fractional order PID (FOPID) controller [19,20] has been introduced by the transfer function of $k_p + (k_i/s^{\lambda})$ or $k_p(1 + (k_i/s^{\lambda}))$, where k_p and k_i are the proportional and integral coefficients and λ denotes the fractional order, which is limited between 0 and 2 [21]. Due to applying the extra control parameter as λ in the FOPI controller function in comparison with the conventional PI controller, the better control action via using this type of controller has been reached [22,23]. In recent decades, many different methods have been presented in the literatures for designing FOPI controllers. Most of these methods are based on satisfaction of the frequency domain specifications including phase margin, gain limitation and robustness to the gain variations at cross-over frequency [21,24–27]. For approximating the fractional term as s^{λ}, the Oustaloup recursive approximation (ORA) algorithm [26] has been suggested. Meanwhile, for modeling the result of ORA approximation in the discrete SIMULINK process, the discretization method via applying the finite impulse response (FIR) filters [28] has been presented. The direct recursive discretization of Tusin operator for estimating the discrete FO[PI] model is proposed in [29], which is easier than implementing the ORA approach.

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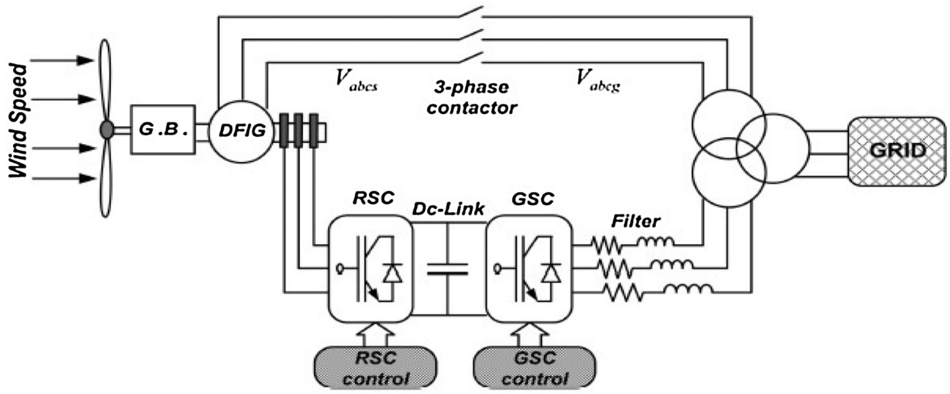

Fig. 1. Schematic diagram of the grid connected DFIG.

In this study, the FOPI is designed for the pitch compensation control loop in the DFIG pitch angle control block. The proposed controller would be substituted with the conventional PI controller to enhance the pitch angle profile derived by the open loop pitch servo control. The direct effect of using the fractional control scheme is revealed in the DFIG active power and rotor speed profiles at high wind speed of 18 m/s considering 15% turbulence intensity in the test system. In the next stage, different symmetrical and asymmetrical transient faults are forced in the point of common coupling (PCC) of DFIGs to compare the efficacy of the FOPI controller with the PI controller. In the remainder of this paper, DFIG is briefly introduced in Section 2, then the design method and discretization equations for the FOPI are presented in Section 3. The compared simulation results are obtained in Section 4 and finally, the conclusions are collected in Section 5.

2. A brief introduction about DFIG

The schematic diagram of the grid connected DFIG is shown in Fig. 1 [30]. The main task of rotor side converter (RSC) is based on controlling DFIG active and reactive powers, whereas the basic aim for applying a grid side converter (GSC) is keeping the DC link voltage constant at rated value. The variations in DC link voltage are caused by changes of current flow direction in the rotor circuit due to reduction or increase in wind speed amounts. On the other hand, pitch angle control loop limits aerodynamic power produced by wind turbine at high wind speeds via increasing the blade pitch angles to prevent overloading on DFIG. At low wind speeds, the blade pitch angles are set to zero for extracting the maximum wind power [31]. Therefore, it is too important to apply this control block in DFIG, especially by designing an intelligent control [32]. The comprehensive models of DFIG comprising the electrical, mechanical and aerodynamic equations are presented in [3,9,12]. In the grid connected operating mode of DFIG, using the hydro-viscous element between the wind turbine rotor and the grid has been suggested for the megawatt scale [33].

Fig. 2 shows the comprehensive pitch angle control loop in DFIG simulated by MATLAB software [15]. As shown, there are two control loops including a rotor speed control via the proportional controller (k) and an active power control named pitch compensation via the PI controller for extracting β_{ref}. According to this figure, by reduction/increase in wind speed value or occurrence of transient faults, the rotor speed error comparing to its reference value (ω_{ref}) and also, DFIG active power deviation compared with the nominal value of 1 p.u. are derived to create the β_{ref} profile for pitch angle control. The produced power by wind turbine is directly related to the power coefficient (C_p), whereas there is a direct highly nonlinear correlation between the pitch angle and the power coefficient [12]. Therefore, to control the active power as well as the rotor speed in different contingencies at high wind speeds, the pitch angle variation has an important impact. In the experimental platform, the PI controller is also proposed after deriving the active power deviation and sending this error to the pitch system [34]. The pitch servo model as the first order function is expressed by Eq. (1) [35].

$$\frac{\beta}{\beta_{ref}} = \frac{1}{\tau_\beta s + 1} \tag{1}$$

where τ_β is the pitch time constant depending on the pitch actuator.

3. Designing and applying FOPI in pitch angle control loop

In the majority of design case studies, three main frequency specifications are used to design FOPI parameters, as follows [21]:

$$\begin{aligned} &Arg[C(j\omega_c)P(j\omega_c)] = -\pi + \varphi_m,\\ &\tfrac{d}{d\omega}[Arg(C(j\omega)P(j\omega))]|_{\omega=\omega_c} = 0,\\ &|C(j\omega_c)P(j\omega_c)| = 1 \end{aligned} \tag{2}$$

where Arg means the angle of the complex function of $C(j\omega_c)P(j\omega_c)$, ω_c and φ_m are respectively the specific chosen crossover frequency and phase margin, $C(j\omega_c)$ indicates the FOPI controller function as $k_p(1 + k_i(j\omega_c)^{-\lambda})$ and $P(j\omega_c)$ is the pitch control model as $1/(1 + j\tau_\beta\omega_c)$.

Solving these three equations, simultaneously, would conclude Eq. (3) as two non-linear formulas between k_i and λ and then, Eq. (4) could be applied for calculating the proper amount of k_p [21].

$$\begin{aligned} &k_i = \frac{-\tan(\arctan(\omega_c\tau_\beta) + \varphi_m}{\omega_c^{-\lambda}[\sin(0.5\lambda\pi) + \cos(0.5\lambda\pi)\tan(\arctan(\omega_c\tau_\beta) + \varphi_m)]},\\ &k_i = \frac{-D \pm \sqrt{D^2 - 4C^2\omega_c^{-2\lambda}}}{2C\omega_c^{-2\lambda}},\\ &C = \frac{\tau_\beta}{1 + (\omega_c\tau_\beta)^2},\\ &D = 2C\omega_c^{-\lambda}\cos(0.5\lambda\pi) - \lambda\omega_c^{-\lambda-1}\sin(0.5\lambda\pi) \end{aligned} \tag{3}$$

$$k_p = \frac{\sqrt{1 + (\omega_c\tau_\beta)^2}}{\sqrt{(1 + k_i\omega_c^{-\lambda}\cos(0.5\lambda\pi))^2 + (k_i\omega_c^{-\lambda}\sin(0.5\lambda\pi))^2}} \tag{4}$$

By drawing the two nonlinear equations between k_i and λ presented by (3) in one plot with regard to the variations of λ from 0 to 2 in the horizontal axis, the intersection points (common points) of two curves would extract the proper values for k_i and λ. Using these values in (4) results in the k_p value. It is noticeable that for designing FOPI in DFIG, the initial guesses for parameters could be derived via (3) and (4). According to the important point that different equipment is available in the test system including cables, transformers and transmission line, which directly affect the dynamic behavior of DFIGs; thus, a proper solution to find the best values for the controller parameters is based on obtaining different simulation results in the test system (described in Section 4) considering the high wind speed of 18 m/s and turbulence intensity as 15%. Moreover, various balanced and unbalanced transient