A robust new full control strategy without FOANR based on substitution method against nonlinear DFIG model for wind application

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ABSTRACT

In order to control the output power of wind application (WA) based on doubly fed induction generator (DFIG). The simple control (SC) strategy based on approaches via flux orientation and neglecting resistance (FOANR) to decoupled axes is the most common used in many previous studies, However this strategy FOANR present a linear synthesis, mainly to control DFIG simple model sensitive to internal and external disturbances, This research paper contribute to developed a robust new full control (FC) strategy based on substitution method (SM) to solving nonlinear coupled axes without FOANR to control nonlinear DFIG model, we use a proportional-integral (PI) controller by the most efficient method: indirect with double loop on each axis to control powers generated by DFIG and stator current directly, we check its performance and efficient compared to the same controller based on flux FOANR against DFIG nonlinear model.

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1. INTRODUCTION

The switch to clean energy has become an imperative, even if with an exponential slight increase over time. This increasing appear by using solar and wind energies which are the most common in field of renewable energy due to evolution of power electronic science and control strategies, for respond to the requirements of performance effectiveness at the lowest possible cost.

The clear proof of this is the using of a doubly fed induction generator (DFIG) in wind application application (WA), after several drawbacks in other kind generators ,squirrel cage induction generator (SCIG) permanent magnet synchronous generator (PMSG) ,related mainly to the performance against wind speed variation and the high cost of power converter, the DFIG driven by wind system configuration to convert the wind energy at the turbine to mechanical energy this energy transformed into electrical energy by the double fed induction generator DFIG provides many advantages ,the DFIG operate at variable speed ±30% range around, the generator’s nominal speed [1], at double benefit :the first is a lower cost of converters due to its connect to low magnitude energy of the rotor [2]. The second is the double operation: and this low energy, which was lost in previous wind generators, It has been transferred to the grid when the DFIG operate Hypersynchronous at higher mechanical speed than the grid speed.

However, all these advantages, DFIG represent a complex system especially In order to control it because the DFIG model it really is a nonlinear synthesis express it by nonlinear differential equations with variable constants, This is what make the first previous studies [3]-[5].to create and uses a simple control based on flux orientation and neglecting resistance (FOANR) leads require grid stability for linearize the DFIG function to obtain a linear synthesis with decoupled axis (d,q), using to make a simple DFIG model and to develop also the simple control (SC) law. With this defect of using a simple model that does not reflect the DFIG real model another drawback is that several studies [6]-[8] use this linear synthesis FOANR for a nonlinear controller like sliding mode [9], [10] only against simple model of DFIG. One of the first, use it a nonlinear synthesis of nonlinear model for more and better performance against reality. These approaches, neglecting stator resistance using by previous researches under hypothesis that the generator is of high power, however if so, actually it has low resistance only but not neglected. Thus, the study is far from reality.

However, there are studies not neglecting stator resistance by [11].but based on flux oriented along d axis by neglecting the quadratic flux under hypothesis of voltage grid stability, this is the main remaining defect which is solved only in this paper, because while the DFIG is connected to the grid, the stator flux in both axis (d,q) it's not careless is the reason why the controller was not responding effectively under unbalance grid conditions [11] or parametric variation especially stator resistance [12] Which not has an input into the SC. Hence these perturbation creates some errors estimation in the input of the controller which is normally sized to support simple model according to the previous approaches as we know it's not reflect the realty.

This research paper solved (d,q) coupled axes by substitution method (SM) and as a result the less efficient performance drawbacks of SC strategy in previous studies by developing a nonlinear synthesis according to the DFIG nonlinear model without FOANR, to control generated active and reactive power by feeding the rotor side converter RSC of DFIG and control stator current directly without estimation reverser to simple control, and for more robustness we chose and apply PI controller with power loop which is inspired previous nonlinear synthesis full control (FC), and to verify its efficiency and performance, and to find out also the defect of the previous one SC, we compared it with the same controller against DFIG nonlinear model.

2. NONLINEAR MODEL OF DFIG

The nonlinear model of DFIG can expressed through expression of stator, rotor voltages and flux components as follows [13]-[18].

$$\begin{cases} v_{ds} = R_s i_{ds} + \frac{d\phi_{ds}}{dt} - \omega_s \phi_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d\phi_{qs}}{dt} + \omega_s \phi_{ds} \\ v_{dr} = R_r i_{dr} + \frac{d\phi_{dr}}{dt} - \omega_g \phi_{qr} \\ v_{qr} = R_r i_{qr} + \frac{d\phi_{qr}}{dt} + \omega_g \phi_{dr} \end{cases} \quad (1)$$

Where:

$$\omega_g = \omega_s - \omega_r \quad (2)$$

$$\begin{cases} \phi_{ds} = L_s i_{ds} + M i_{dr} \\ \phi_{qs} = L_s i_{qs} + M i_{qr} \\ \phi_{dr} = L_r i_{dr} + M i_{ds} \\ \phi_{qr} = L_r i_{qr} + M i_{qs} \end{cases} \quad (3)$$

the powers generated by DFIG can expressed by (4).

$$\begin{cases} P_s = V i_{ds} + V_{qs} i_{qs} \\ Q_s = V_{qs} i_{ds} - V_{ds} i_{qs} \end{cases} \quad (4)$$

3. DFIG MODEL BASED ON SUBSTITUTION METHOD

The previous studies using FOANR [19]-[21] to developed simple model of DFIG, However, this is the first time [22] that it has not been used to express the nonlinear model of DFIG [23] and later we use this nonlinear synthesis for PI linear controller.

$$\begin{cases} V_{ds} = R_s i_{ds} + L_s \frac{di_{ds}}{dt} + M \frac{di_{dr}}{dt} - \omega_s \phi_{qs} \\ V_{qs} = R_s i_{qs} + L_s \frac{di_{qs}}{dt} + M \frac{di_{qr}}{dt} + \omega_s \phi_{ds} \\ V_{dr} = R_r i_{dr} + L_r \frac{di_{dr}}{dt} + M \frac{di_{ds}}{dt} - \omega_g \phi_{qr} \\ V_{qr} = R_r i_{qr} + L_r \frac{di_{qr}}{dt} + M \frac{di_{qs}}{dt} + \omega_g \phi_{dr} \end{cases} \quad (5)$$

We can determine the expression of the rotor current variation in the stator by using equation system (5).

$$\begin{cases} \dot{I}_{dr} = \frac{1}{M}\left[V_{ds} - R_s i_{ds} - L_s \dot{I}_{ds} + \omega_s \phi_{qs}\right] \\ \dot{I}_{qr} = \frac{1}{M}\left[V_{qs} - R_s i_{qs} - L_s \dot{I}_{qs} - \omega_s \phi_{ds}\right] \end{cases} \quad (6)$$

We may also establish the formulation of the rotor current fluctuation in the rotor by applying in (5):

$$\begin{cases} \dot{I}_{dr} = \frac{1}{L_r}\left[V_{dr} - R_r i_{dr} - M \dot{I}_{ds} + \omega_g \phi_{qr}\right] \\ \dot{I}_{qr} = \frac{1}{L_r}\left[V_{qr} - R_r i_{qr} - M \dot{I}_{qs} - \omega_g \phi_{dr}\right] \end{cases} \quad (7)$$

we can determine the variation of the stator current by substituting (6) in (7), which is directly related to the rotor voltages.

$$\begin{cases} \dot{I}_{ds} = \frac{1}{L_r \delta_1} V_{dr} + \frac{1}{\delta_1 L_r}\left(\omega_g \phi_{qr} - R_r i_{dr}\right) + \frac{1}{M \delta_1}\left(R_s i_{ds} - V_{ds} - \omega_s \phi_{qs}\right) \\ \dot{I}_{qs} = \frac{1}{L_r \delta_1} V_{qr} - \frac{1}{\delta_1 L_r}\left(\omega_g \phi_{dr} + R_r i_{qr}\right) + \frac{1}{M \delta_1}\left(R_s i_{qs} - V_{qs} + \omega_s \phi_{ds}\right) \end{cases} \quad (8)$$

Where:

$$\delta_1 = \frac{M}{L_r} - \frac{L_s}{M} \quad (9)$$

by applying the laplace transform to the previous in (8). We can obtain the objective we wanted, namely to find the Transfer function that relates the rotor voltage to the stator current, as shown in (10).

$$\begin{aligned} V_{qr} &= \left[\frac{S.M L_r \delta_1 - R_s L_r}{M}\right] i_{qs} + \left(R_r i_{qr} + \omega_g \phi_{dr}\right) - \frac{L_r}{M}\left(\omega_s \phi_{ds} - V_{qs}\right) \\ V_{dr} &= \left[\frac{S.M L_r \delta_1 - R_s L_r}{M}\right] i_{ds} + \left(R_r i_{dr} - \omega_g \phi_{qr}\right) + \frac{L_r}{M}\left(\omega_s \phi_{qs} + V_{ds}\right) \end{aligned} \quad (10)$$

For simplicity, we put the following:

$$\begin{cases} G_{qr} = R_r i_{qr} + \omega_g \phi_{dr} - \frac{L_r}{M}\left(\omega_s \phi_{ds} - V_{qs}\right) \\ G_{dr} = R_r i_{dr} - \omega_g \phi_{qr} + \frac{L_r}{M}\left(\omega_s \phi_{qs} + V_{ds}\right) \end{cases} \quad (11)$$

Based on (10) and (11), The nonlinear model based on the substitution method can be developed without using FOANR as shown in Figure 1. After solving the nonlinear system problems between rotor voltages and stator currents, we need to solve the nonlinear problem with (d,q) axis coupling between stator currents and powers in (4).

3.1. Expression of powers based on substitution method

The stator currents of the axes "d" and "q" are determined from the active power (4) as follows:

$$\begin{cases} i_{ds} = \frac{1}{V_{ds}}\left[P_s - V_{qs} i_{qs}\right] \\ i_{qs} = \frac{1}{V_{qs}}\left[P_s - V_{ds} i_{ds}\right] \end{cases} \quad (12)$$

in the same way the stator currents of the axes "d" and "q" can be determined from the reactive power (4) as follows:

$$\begin{cases} i_{ds} = \frac{1}{V_{qs}}\left[Q_s + V_{ds} i_{qs}\right] \\ i_{qs} = \frac{1}{V_{ds}}\left[V_{qs} i_{ds} - Q_s\right] \end{cases} \tag{13}$$

as a result, we substitute equation (12) in (13) and obtain the expression that connects the statoric currents to the coupled powers, allowing us to control the active power along the "q" axis and the reactive power along the "d" axis.

$$\begin{cases} P_s = V_{ds} V_{sc1} i_{qs} + V_{sc} Q_s \\ Q_s = V_{qs} V_{sc1} V_{sc} i_{ds} - V_{sc} P_s \end{cases} \tag{14}$$

Where:

$$V_{sc} = \frac{V_{ds}}{V_{qs}} \text{, and } V_{sc1} = \frac{1}{V_{sc}} + V_{sc} \tag{15}$$

V_{sc}: ratio of stator voltage or coupled grid active and reactive power measured in the Park (d,q) reference frame.
V_{sc1} : ratio of stator voltage or coupled gridactive and reactive power in the Park (d,q) reference frame.

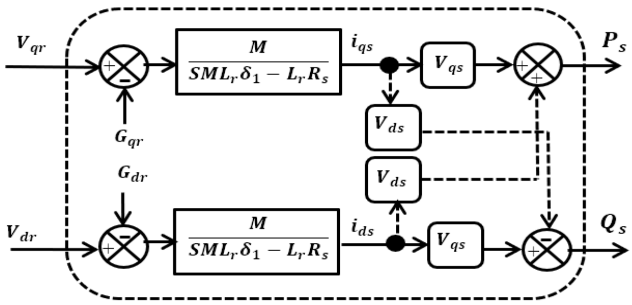

Figure 1. Nonlinear model without FOANR based on substitution method

4. CONTROL OF DFIG USING PI DOUBLE LOOP BASED ON SUBSTITUTION METHOD

In this control Figure 2 we use previous nonlinear synthesis of DFIG nonlinear model equation (10) to developed PI full controller without FOANR and with the common efficient method which has double loop control direct loop for the active and reactive power and also indirect loop for directly control quadratic and direct sartor current, on each axis we use double PI controller.

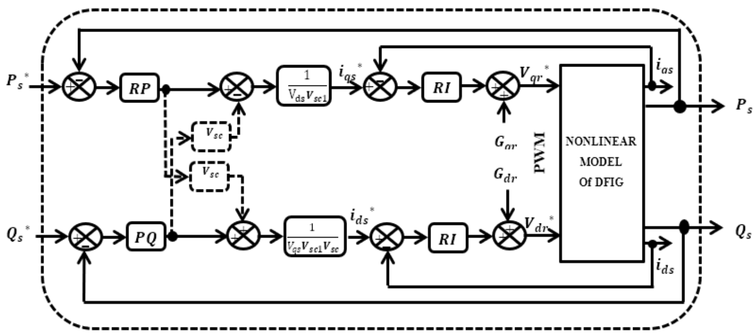

Figure 2. Block diagram of PI full control with double loop based on substitution method

4.1. Indirect stator current loop (FC)

Using the nonlinear model (8), the control synthesis can be determined using the PI controller of the stator current in each axis (d, q) as shown in Figure 3. The transfer function can develop Figure 3 corresponds to the current regulators (RI) is given by $(K_p + \frac{K_i}{s})$ in Figrue 2, the open loop transfer function (OLTF).

$$OLTF = \frac{S+\frac{K_i}{K_p}}{\frac{S}{K_p}} \frac{\frac{M}{ML_r\delta_1}}{\left(S-\frac{L_rR_S}{ML_r\delta_1}\right)} \tag{16}$$

We choose the pole compensation method in order to eliminate the zero of the transfer function leads to the following equality [24], [25].

$$\frac{K_i}{K_p} = -\frac{R_s}{M\delta_1} \tag{17}$$

The OLTF is obtained:

$$OLTF = \frac{K_p}{SL_r\delta_1} \tag{18}$$

The closed loop transfer function (CLTF) It is given as follows:

$$CLTF=\frac{1}{1+\tau S} \tag{19}$$

τ for response time. So CLTF it can be expressed in (20).

$$CLTF=\frac{1}{1+\tau S} = \frac{1}{1+\frac{1}{OLTF}} \tag{20}$$

By identification we find that:

$$K_p = \frac{L_r\delta_1}{\tau}, K_i = \frac{-R_sL_r}{M.\tau} \tag{21}$$

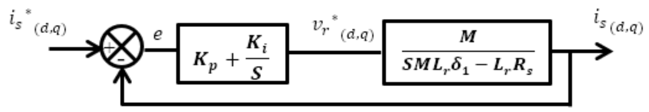

Figure 3. Indirect loop regulated by PI full controller

4.2. Direct power loop (FC)

For a direct control of the powers, we substitute (14) in (10), that the voltages related to the powers by a first order transfer function:

$$\begin{cases} V_{qr} = \left(\frac{ML_r\delta_1S-L_rR_S}{MV_{ds}\,V_{sc1}}\right)P_s + \frac{L_rR_sV_{sc}}{MV_{ds}\,V_{sc1}}Q_s + \overbrace{\left(R_ri_{qr} + \omega_g\phi_{dr}\right) - \frac{L_r}{M}\left(\omega_s\phi_{ds} - V_{qs}\right)}^{G_{qr1}} \\ V_{dr} = \left(\frac{ML_r\delta_1S-L_rR_S}{MV_{qs}V_{sc}\,V_{sc1}}\right)Q_s - \frac{L_rR_s}{MV_{qs}\,V_{sc1}}P_s + \overbrace{\left(R_ri_{dr} - \omega_g\phi_{qr}\right) + \frac{L_r}{M}\left(\omega_s\phi_{qs} - V_{ds}\right)}^{G_{dr1}} \end{cases} \tag{22}$$

in this situation, we can see that the voltage is associated with two transfer functions, as illustrated in Figure 4, where (Kp1+Ki1/S) refers to the RP regulators and (Kp2+Ki2/S) relates to the RQ regulators in Figure 2.

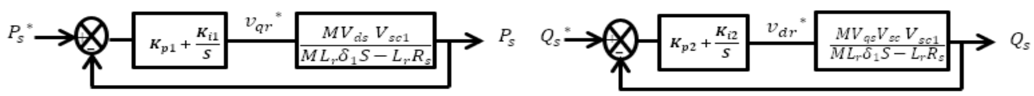

Figure 4. Direct loop for active and reactive power regulated by PI full controller

To determine these controller gains, the same method based on the pole compensation method is used. We fined:

$$\begin{cases} K_{p1} = \frac{L_r\delta_1}{\tau\, V_{ds}V_{sc1}} \quad , K_{i_1} = \frac{-R_sL_r}{\tau M.V_{ds}V_{sc1}} \\ K_{p2} = \frac{L_r\delta_1}{\tau V_{qs}V_{sc}\,V_{sc1}} \quad , K_{i_2} = \frac{-R_sL_r}{\tau M.V_{qs}V_{sc}\,V_{sc1}} \end{cases} \tag{23}$$

Important note: for the simple control (SC) we also used same controller PI indirect with double loop however it based-on flux orientation and negligence resistance (FOANR) as follow equation shown [26]:

$$\begin{cases} R_s = 0 \\ \phi_{qs} = 0 \end{cases} \tag{24}$$

We substituted approximations of equation (24) in all previous equations of the DFIG in order to extract the simple control and compared with our new full control (FC) based on substitution method.

5. RESULTS AND DISCUSSION

5.1. Reference tracking test

In this examination of Figure 5, we will be able to assess the response of each PI-SC and PI-FC controller based on the required power value. This test is done in the absence of any internal disturbance, namely the variations in machine parameters; and external which are the variation in wind speed, as well as the disturbance in the voltage of the electrical network in which the DFIG is connected. The results showed a superiority of the PI-SC method compared to that with PI-FC in terms of tracking response.

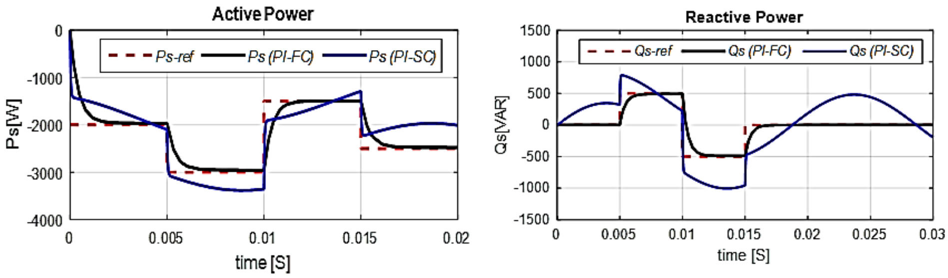

Figure 5. Powers reference tracking test

5.2. Robustness Tests

We check the performance and efficient of the controller PI-FC and PI-SC against nonlinear model, to control powers generated by DFIG, by double testing: the first one is under saturation of magnetic circuit, when the Magnetizing inductance, increase by 5% of nominal value Figure 6. The second one under a rise rotor and stator resistances Rr, RS+50% of nominal value Figure 7, The latter (stator resistance) is very important because it has no input in the simple controller (PI-SC), due to neglecting, and this give to our study more reliability and accuracy in reality.

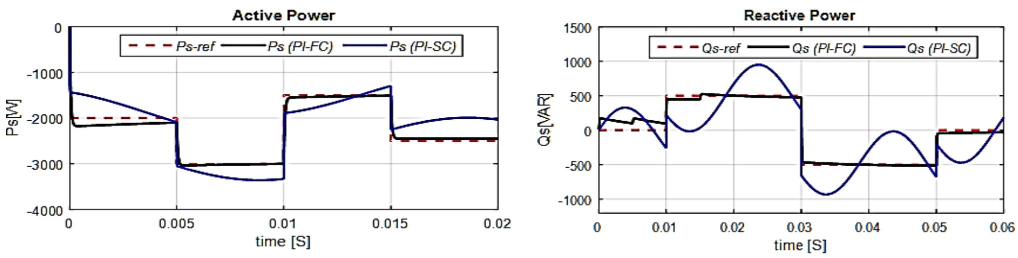

Figure 6. Powers and current response under saturation of magnetic circuit (M+5%)

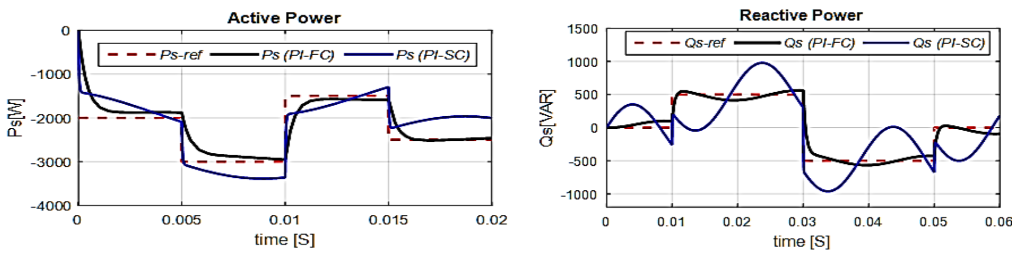

Figure 7. Power and current response under (Rr, Rs+50%)

5.3. Sensitivity to Perturbations

The results figure 8, appears that the simple control PI-SC is more affected by both change: The active and reactive value represents higher peak amplitude during wind speed variation t=4s. It can be seen that also the reactive power has another peak amplitude t=3s related to time of oscillatory active power, with presence of low power quality especially following a start-up (generator) dependent on the level of the wind generator DC link voltages under simple control which not reflect the DFIG real model.

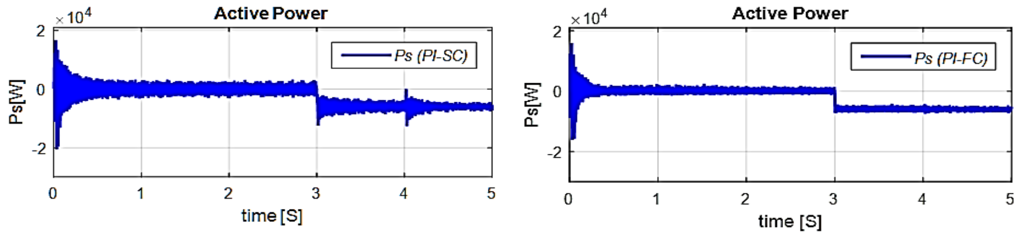

Figure 8. Active power response to a speed variation and changing power

6. CONCLUSION

In this article we demonstrated the effectiveness of our new full control strategy based on substitution method against the DFIG real model using classical PI with double loop method, comparing with same controller method that based on flux orientation and neglecting resistance, as the results showed a high response to PI-FC under changing conditions with different challenge. In fact, the PI-SC its performance is not badly without previous challenge perturbation under highly response, but lacked some improvement to match the DFIG real model and to respond highly according to wind system application, this is what science always seeks and it was achieved in this paper. Depending on the previous results show that our new control strategy is more efficient against DFIG real model, nevertheless the recent studies still based on simple strategy by flux orientation and neglecting resistance, besides, our strategy is valid for all other control system, wind based on other generator control PV solar, machines, and all applications with coupled axes problems.

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