INERTIAL RESPONSE USED FOR A SHORT TERM FREQUENCY CONTROL FOR DFIG WIND TURBINE CONTROLLED BY ADRC

Rachid Chakib\(^1\), Mohamed Cherkaoui\(^1\) and Ahmed Essadki\(^2\)
\(^1\)Department of Electrical Engineering, Mohammedia School of Engineers (EMI), Rabat, Morocco
\(^2\)Department of Electrical Engineering of High School of Technical Education (ENSET) - Rabat Mohammed V University in Rabat, Morocco
E-Mail: RachidChakib@research.emi.ac.ma

ABSTRACT

In this paper, we study the behavior of the wind turbine at variable speed controlled by the control loops of ADRC (Active Disturbance Rejection Control) when a fault is affecting the grid frequency. Since the rotational speed is decoupled from the frequency by converters connecting the rotor and the grid, the inertial response of the system is substantially zero, and therefore does not naturally participate in the frequency setting. In this paper, we propose in this paper a control strategy that can, in case of frequency drop, release some of the kinetic energy stored in the turbine at the beginning of the fault and thus provide additional power to support the grid. The performance of this control strategy is also studied for the various values of the gain of the control loop of the inertial response of system. The dynamic model of this wind system based on a DFIG, the ADRC controllers and the control loop of inertial response of the system are simulated in Matlab-Simulink environment.

Keywords: ADRC, inertial response, DFIG, frequency control, MPPT.

1. INTRODUCTION

Today, wind energy is well established in the field of electric power producers. The intermittent nature of wind power production and the increase of its penetration rate in power systems generate several problems for operators such as voltage variation, frequency variation and grid instability\([1, 2]\). The network operators impose some attachment requirements on the distribution grid of power plants. During a frequency variation, the wind turbine must first stay connected to the grid and function normally and must also provide active power to help restore the frequency to its nominal value \([1, 2, 3]\). The frequency is a global variable that is identical throughout the grid. Its value must remain within a very small range of variation to ensure a normal and optimal operation of electrical equipment connected to the grid. The frequency setting is the result of the balance between production and consumption of active power \([4, 7]\).

In this paper, we study the behavior of a variable speed wind turbine system based on the DFIG and controlled by the control loops of ADRC during a variation of grid frequency. The stator of the DFIG is directly connected to the grid and function normally and must also provide active power to help restore the frequency to its nominal value \([1, 2, 3]\). The frequency is a global variable that is identical throughout the grid. Its value must remain within a very small range of variation to ensure a normal and optimal operation of electrical equipment connected to the grid. The frequency setting is the result of the balance between production and consumption of active power \([4, 7]\).

In this paper, we study the behavior of a variable speed wind turbine system based on the DFIG and controlled by the control loops of ADRC during a variation of grid frequency. The stator of the DFIG is directly connected to the grid and the rotor is connected to the grid through two electronic power converters separated by a linking DC bus. The grid side converter is connected to the latter by means of a three-phase filter for filtering the current harmonics (Figure-1) \([5, 6]\).

2. DFIG WIND TURBINE CONTROLLED BY ADRC

By choosing Park’s referential linked to the rotating stator field and by directing the stator flux along the d-axis, the mathematical model of DFIG is given by the following equations \([5, 6, 8]\):

\[
V_{sd} = R_s i_{sd} + \frac{d\phi_{sd}}{dt}
\]
V_{sq} = R_{s}i_{sq} + \omega_{r}\Phi_{sd} \tag{2}

\frac{d i_{rd}}{dt} = -\frac{R_{r}}{\sigma_{r}}i_{rd} + \omega_{r}i_{rq} + \frac{1}{\sigma_{r}}V_{rd} \tag{3}

\frac{d i_{rq}}{dt} = -\frac{R_{r}}{\sigma_{r}}i_{rq} - \omega_{r}i_{rd} - \frac{I_{m}}{\sigma_{r}\sigma_{q}}\Phi_{s} + \frac{1}{\sigma_{r}}V_{rq} \tag{4}

T_{em} = -\frac{3}{2}pI_{m}\Phi_{s}i_{rq} \tag{5}

P_{s} = -V_{sq}\frac{I_{m}}{\sigma_{q}}i_{rq} \tag{6}

Q_{s} = \frac{V_{sq}\Phi_{s}}{\sigma_{s}} - \frac{V_{sq}I_{m}}{\sigma_{s}}i_{rd} \tag{7}

Where \sigma = 1 - \frac{i_{m}^{2}}{\sigma_{q}\sigma_{r}} is dispersion coefficient between the coilings d and q.

Modeling in dq reference of the set of binding to the electric grid consisting of the DC bus, the grid side converter and the filter are given by the equation below:

\frac{d i_{df}}{dt} = \frac{1}{\sigma_{f}}V_{sd} - \frac{R_{f}}{\sigma_{f}}i_{df} - \omega_{s}i_{qf} - \frac{1}{\sigma_{f}}V_{df} \tag{8}

\frac{d i_{qf}}{dt} = \frac{1}{\sigma_{f}}V_{sq} - \frac{R_{f}}{\sigma_{f}}i_{qf} + \omega_{s}i_{df} - \frac{1}{\sigma_{f}}V_{qf} \tag{9}

2U_{dc}\frac{di_{df}}{dt} = \frac{3}{C_{d}^{2}}i_{qf} - \frac{2U_{dc}}{C}i_{mr} \tag{10}

Where \(U_{dc}\) is DC bus voltage.

After starting, the control strategy is designed to maximize wind energy converted by imposing a torque reference given by a power maximization algorithm MPPT (maximum Power Point Tracking) \[16\].

\[ T_{em,MPPT} = \frac{1}{2} C_{p_{max}} \rho \pi R^{5} \frac{\Omega_{mec}^{3}}{\lambda_{opt}^{2}} \tag{11} \]

R is the radius of the turbine, \(\rho\) is the air density, \(\Omega_{mec}\) is the mechanical rotor speed, \(\lambda_{opt}\) is the optimum value of the speed ratio which corresponds to a maximum power coefficient \(C_{p_{max}}\). \(G\) is the coefficient multiplier.

The electromagnetic torque and the reactive power of the DFIG are independently controlled by the converted rotor side. The rotor currents are controlled by two ADRC controllers that determine the reference of rotor voltages to be applied. The rotor current in the q-axis allows to control the electromagnetic torque and the one in the d-axis is used to control the reactive power \[6\].

\[ i_{rq,ref} = -\frac{2}{3\rho \mu_{0} \sigma_{q}} T_{em,MPPT} \tag{12} \]

\[ i_{rd,ref} = \frac{\Phi_{s}}{L_{s}} - \frac{L_{r}}{V_{sq} I_{m}} Q_{s,ref} \tag{13} \]

\[ Q_{ref} \rightarrow \text{ADRC} \rightarrow V_{ref} \rightarrow 2 \rightarrow P \rightarrow W \rightarrow M \rightarrow R \rightarrow S \rightarrow C \text{ Figure-2. Control loops of rotor currents.} \]

\[ i_{df,ref} = \frac{2}{3V_{dc}} Q_{f,ref} \tag{14} \]

\[ i_{qf,ref} = C_{ADRC}(U_{dc} - U_{dc,ref}) \tag{15} \]

\[ C_{ADRC}: \text{equation of ADRC controller.} \]

\[ Q_{ref} \rightarrow \text{ADRC} \rightarrow V_{ref} \rightarrow \frac{1}{3} \rightarrow P \rightarrow G \rightarrow W \rightarrow S \rightarrow C \text{ Figure-3. Control of grid side converter.} \]

Mechanical speed is determined from the dynamic equation applied to the generator rotor.

\[ \frac{T_{aero}}{G} - T_{em,MPPT} = \int \frac{d\Omega_{mec}}{dt} \tag{16} \]

\(T_{aero}\): aerodynamic torque

3. System Maintainability Against Frequency Variation

The speed of the DFIG is controlled by the rotor side converter and is adapted according to the wind speed in order to extract the maximum power \[13, 14\].

\[ \Omega_{mec} = \frac{\lambda_{opt} \Omega_{p} \rho}{R} \tag{17} \]

Where \(\rho\) is the wind speed.

To evaluate the behavior of the DFIG during a frequency drop of 0.2 Hz/s between \(t=15\) s and \(t=20\) s, we...
consider the wind speed constant and equals 10m/s, and the blade pitch angle is zero ($\beta = 0$). The parameters of the simulated wind system in Matlab-Simulink environment as well as the parameters of regulators are given in the appendix.

We find that the variation of frequency has very little influence on the speed of the DFIG. The compensation of the variation of the stator rotating field by that of the rotor rotating field keeps the mechanical speed to its reference value.

By imposing an electromagnetic torque reference $T_{em_{MPPT}}$ on the generator, the turbine speed is stabilized, in steady regime, around an optimum speed allowing maximum power extraction from the wind.
It is found that the variation of frequency does not cause the generator in unstable operation, or an operating point requiring decoupling of the machine. All electrical and mechanical parameters of the generator perfectly follow their setpoints exactly as before the fault appears.

The variable speed wind turbine based on DFIG is not practically affected by variation of the grid frequency. Therefore, it has a very low inertial response and thus does not participate in maintaining the frequency [8, 10].

4. INERTIAL RESPONSE OF DFIG TO A FREQUENCY CONTROL

4.1 Principle

The variable speed wind turbine includes rotating masses (turbine and generator shaft) that store kinetic energy. Due to the presence of the electronic power interface between the DFIG and the grid, the natural inertia can not be used because the turbine speed does not depend on the grid frequency. We must therefore adapt the speed control to involve the system inertia in the frequency setting [14].

The method we propose is to generate an additional setpoint of the electromagnetic torque, depending on the derivative of the frequency, added to the electromagnetic torque of the DFIG [2, 7, 8]. This new torque value causes slowing of the mechanical speed of the generator which allows the extraction of the kinetic energy stored in the rotating masses.

\[ T_{em, ref} = T_{em, MPPT} + \Delta T_{em} \]  \hspace{1cm} (18)

Figure-11. Reactive stator power.

\[ \frac{df}{dt} < 0 \Rightarrow \frac{T_{\text{aero}}}{g} - T_{em, ref} = \frac{d\Omega_{\text{mec}}}{dt} < 0 \]  \hspace{1cm} (19)

It is assumed that losses in the turbine, the gearbox and the generator shaft are zero; the maximum electrical power generated by the turbine is expressed as follows:

\[ P_{e,\text{MPPT}} = \frac{1}{2} C_{p\text{max}} \rho R^5 \frac{\Omega_{\text{a}}^8}{\lambda_{opt} g^2} \]  \hspace{1cm} (20)

The mechanical equation applied to the generator rotor is expressed on a per-unit basis:

\[ \Delta T_{em, pu} = \left( \frac{\Omega_{\text{a}}}{\Omega_{pu}} \right)_{pu} - T_{em, pu} = f \frac{\Omega_{\text{a}}}{\rho_{\text{nom}}} \frac{d\Omega_{\text{mec, pu}}}{dt} \]  \hspace{1cm} (21)

Where \( \Omega_{\text{nom}} \) and \( P_{\text{nom}} \) are respectively the nominal speed and nominal power of the generator.

The wind system inertia constant reduced to the generator shaft is defined by:

\[ H = \frac{1}{2} \Omega_{\text{a}} \rho_{\text{nom}} \]  \hspace{1cm} (22)

The inertial power injected into the grid in the first seconds after the frequency drop is expressed by the following formula:

\[ \Delta P_{e, pu} = 2 H f_{pu} \frac{df_{pu}}{dt} \]  \hspace{1cm} (23)

\[ f_{pu} = \frac{f}{f_{0}} \text{: Grid frequency on a per-unit basis.} \]

The additional electromagnetic torque proportional to the derivative of the frequency drop which has to be introduced into the control loop of wind system is expressed by:

\[ \Delta T_{em, pu} = 2 H f_{pu} \frac{df_{pu}}{dt} \frac{1}{\Omega_{\text{mec, pu}}} \]  \hspace{1cm} (p.u)  \hspace{1cm} (24)

This additional torque is directly added to the reference of the electromagnetic torque resulting from the MPPT control aiming to maximize the power as shown in Figure-12 below.
The first order block is used to determine the derivative of the frequency and the time constant $T_{ref}$ minimizes the impact noise of the frequency signal measured. The gain $K_{ri}$ determines the amount of additional wind power injected after the frequency drop [2, 4].

According to the above diagram, the inertial response of wind power is expressed on a per-unit basis by the following equation:

$$\Delta P_{e,p.u} = 2H \left( \frac{K_{ri}}{T_{ref} + 1} f_{pu}(\text{p.u}) \right)$$

(25)

In case of frequency decline $\frac{df}{dt} < 0$, the calculated additional torque is negative and the reference electromagnetic torque $T_{em,ref}$ increases, which leads to a slower speed of rotation of the turbine and hence to the extraction of kinetic energy stored in rotating masses [2, 14].

4.2 Evaluation of frequency control performance by inertial response

To evaluate the performance of this frequency control by the inertial response, we simulated the wind system whose parameters are given in the appendix during a frequency drop of 0.2 Hz/s from $t=15s$ to $t=20s$ (Figure-4). The wind speed is considered constant and equal to 10m/s and the blade pitch angle is assumed zero. It is also assumed that the electrical machine and its control system are perfect and therefore, whatever the power generated, the developed electromagnetic torque is at all times equal to its reference value.

The electromagnetic torque is controlled at its reference value imposed by the MPPT control to extract maximum power from the wind. When frequency decreases from $t=15s$, an additional torque and proportional to the derivative of frequency is added to the initial value of the reference torque which causes an increase in the electromagnetic torque of the DFIG, hence the change of point operating wind system (Figure-13). When the frequency stabilized from the time $t=20s$, the additional torque vanishes and the electromagnetic torque of the DFIG gradually regains its initial reference value. The value of the additional torque and its rate of variation during a frequency drop increases with the gain $K_{ri}$.

The rotor speed with the different values of the gain $K_{ri}$ is shown in Figure-14. The rotor rotates at the optimum speed which is adapted to the wind speed according to the MPPT control. At the appearance of the frequency fault at $t=15s$, an additional peak of electromagnetic torque is generated by the DFIG, which causes a drop in the speed of rotation of the turbine. This speed drop releases a portion of the kinetic energy stored in the rotating masses and inject it into the grid.

The greater the gain $K_{ri}$ is getting, the more significant and rapid the speed drop is, enabling to inject more power into the grid. In general, the gain $K_{ri}$ must not exceed a certain limit so that the speed does not decrease.
below the minimum value that ensures correct operation of the turbine.

Figure-15 shows the active power supplied by the wind turbine for different values of the gain $K_{ri}$. At the appearance of the frequency drop, an additional electric power is injected into the network to participate in the stabilization of the frequency. The value of the injected additional power and its rate of variation $\frac{dP_F}{dt}$ vary according to the gain $K_{ri}$. The larger the gain is the more significant the injected power into the grid, allowing avoiding the profound frequency dip.

When the frequency is stabilized from $t= 20s$, wind power transmitted to the grid decreases, which allows the speed of the turbine to increase, to regain its optimum value and to restore the kinetic energy reserve. The greater the gain $K_{ri}$, is the more important the transmitted electric power drop is during the restore speed.

![Figure-15. Active power of DFIG.](image)

![Figure-16. Zoom on active power of DFIG.](image)

5. CONCLUSIONS

In this article, we have been interested firstly in the behavior of the variable speed wind system based on a DFIG during a frequency fault following an imbalance between production and consumption of active power. Secondly, we studied a control strategy of inertial response allowing the wind turbine to participate in maintaining the frequency in the short term by releasing the kinetic energy stored at the beginning of the fault. The studied wind system is controlled by the ADRC control loops.

The wind turbine based on DFIG does not naturally participate in the frequency control due to its rotational speed which is independent on the main frequency. Simulation results showed that the frequency variation has practically no impact on the wind system operating point.

The strategy developed in this paper allows the wind turbine to participate in short term frequency control while ensuring operation at maximum power. In the first instants after the frequency drop, it is the kinetic energy of the rotating masses of wind system that compensates transiently active power imbalance before other conventional production groups begin to intervene. Simulation results were presented to evaluate the performance of this control strategy for the different gain of the inertial response control loop. The greater the gain is the more important additional power injected into the grid at the frequency fault is, which allows to avoid the deep frequency decline.

APPENDIX

Doubly fed induction generator parameters
Rated power 1.5 MW
Stator and rotor resistance: $R_s = 10.3m\Omega, R_r = 8.28m\Omega$
Stator and rotor inductance: $L_s = 27.2401mH, L_r = 27.0777mH$
Mutual inductance: $L_m = 26.96 mH$
Number of pole pairs: $p = 2$

Turbine parameters
Radius of the turbine $R = 39m$
Gain multiplier $G = 70$
Inertia total moment $J = 60Kg.m^2$
Air density $\rho = 1.225Kg/m^2$
Coefficient of viscous friction $f = 0.1$
Optimal tip speed ration $\lambda_{opt} = 8.1$
Maximal power coefficient $C_{pmax} = 0.4655$

Connecting to the grid parameters
Filter inductance $L_f = 2.5mH$
Filter resistance $R_f = 75m\Omega$
DC link capacity $C = 5000\mu F$

ADRC controller parameters
Rotor currents controller gain $K_{p,r} = 100$
Rotor currents parameter $b_{r0} = 2532.2$
Observation parameters of the loop currents rotor $\beta_{tr} = 600, \beta_{2r} = 9e^4$
Filter currents controller gain $K_{p,f} = 300$
Filter currents parameter $b_{f0} = -400$
Observation parameters of the loop currents filter
\[ \beta_{1f} = 1800, \beta_{2f} = 81e^4 \]
DC link voltage controller gain \( K_{p,c} = 100 \)
DC link voltage parameter \( P_{e0} = 3.3941e^5 \)
Observation parameters of the loop DC link voltage
\[ \beta_{1c} = 600, \beta_{2c} = 9e^4 \]

REFERENCES


