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ADRC Performance in Power Control of DFIG used in Wind Turbine During Grid Voltage Fault

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Abstract

This paper presents the performance of Active Disturbance Rejection Control (ADRC) applied to power control of Doubly Fed Induction Generator (DFIG) used in wind turbine during the grid voltage fault such as overvoltage and under voltage.

In the situation of a grid fault, the characteristics of the grid changes and also the wind turbine might lose the connection with the grid. The main objective of this article is to evaluate the ADRC performance, and to propose an improved power control of DFIG during the voltage fault without losing the connection with the grid in case of overvoltage and undervoltage fault.

The improvement method is based on ADRC controller and adding a circuit to protect the vulnerable rotor converters such as a DC Chopper and a Serial Active Crowbar Resistance (SACR).

In this article we synthesize the ADRC controllers applied to turbine, Rotor Side Converter (RSC) and Gride Side Converter (GSC) control strategy. The dynamic model of DFIG and wind system are simulated in Matlab-Simulink environment.

Keywords: *ADRC, DFIG power, wind energy, overvoltage, undervoltage, voltage fault*

1. Introduction

Most of the last research works are interested in renewable energies as they play a key role in solving problems related to electrical energy such as the exhaustion of fosil of fuel and the release of greenhouse gas (global warming) [1].

Wind power is a clean energy and environmentally friendly. This type of energy can contribute significantly to the energy development as it's free, clean and renewable;

In addition, it has great potential and so many wind farms are in service worldwide [2].

Morocco is a great example; the kingdom has priority to develop the wind power on the whole territory for which the kingdom plans to reach a capacity of 2000 MW by 2020 [3].

Studies in the development of wind energy are more interested in DFIG model rather than the electromechanical conversion [13]. The DFIG is largely used in this area for its benefits in the case of operating under variable speed and size of the rotor converters.

However, researchers in the field today are also interested in the efficiency of the electrical energy supply and wind turbines. In fact, a turbine connected to the grid can suffer from the electrical grid fault (such the sudden nominal voltage variation line to line). This type of defect is known in the field of wind energy research as the LVRT [2].

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The main purpose of the studies accomplished in that field is to ensure the protection of the turbine equipments (such as the rotor converters) during grid voltage fault without tripping of the circuit breakers. The parameters of the circuit breakers will be not changed.

In this paper overvoltage and undervoltage fault are applied to DFIG (during voltage fault DC shopper is used for DC voltage limitation, and the Crowbar resistance for fault currents limitation). In literature several works are published about crowbar and DC shopper [2]-[14] (the two components are without effect in normal condition).

2. Voltage Grid Fault

2.1. Power Quality

The power quality is often defined as the electrical network's or the grid's ability to ensure a clean and stable power supply. The power quality covers three concepts:

a. Stable power supply

This aspect covers electrical blackout or interruptions. There are a number of criteria for classifying these blackout, such as scheduled and unscheduled blackout, long (more than 3 minutes) and short blackout (between 1 and 179 second). For blackout of less than 1 second, although the terms "very short black" and "cut-off" are sometimes used, it is generally referred to as voltage dips [4].

b. Voltage wave quality

This aspect covers the disturbances related to the voltage waveform delivered by the grid, which can alter the functioning of the electrical machines connected to the grid, or even damage them. Different terms can be used depending on the characteristics of the disturbance: voltage dips, phase imbalance, pulse over voltages, flicker, high or low voltages, frequency variations, harmonic and inter-harmonic rates, etc. the following figure presents the voltage waves disturbances.

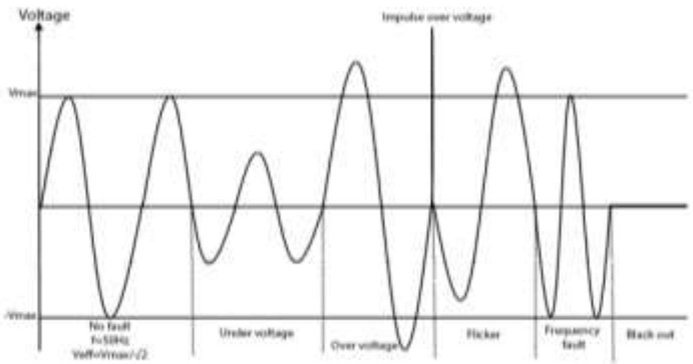

Figure 1. Voltage Waves Disturbances

c. Electrical service Quality

This parameter characterizes the relation between a user and the network operator (emergency response time, commissioning time, connection delay, scheduled shutdown notification, *etc.*,).

2.2. Voltage Wave Quality

The AC power grids are voltage wave delivered by the electrical system ideally takes the form of a sinusoid of frequency and amplitude. However, in reality, the voltage wave is never perfectly sinusoidal, the frequency and the amplitude of this wave constantly varies.

If the variation of voltage wave is more important, the functioning of some electrical machines connected to the grid such as wind turbines, production plants, domestic appliances, industrial machines, may be disturbed. In the most extreme cases, this can range from the impossibility of operating during the duration of the disturbance [5], to long-term material damage or, more rarely, to instantaneous material damage. To sum-up we can distinguish the following grids default type, each disturbance has a specific effect on the network or on the electrical device:

- Voltage dips
- Impulse overvoltage
- Flicker
- Undervoltage
- Overvoltage
- Frequency fluctuation
- Imbalance
- Harmonics and inter-harmonics

2.3. Wind turbine and Voltage Grid Fault

Wind turbines connected to the grid can be badly affected by voltage grid fault even the punctual and smallest ones. This can cause many technical problem and malfunctions to the equipments that need a permanent and sustainable energy supply.

The shut-down of a high-power load such as high voltage motors, high-power engines and Electrical Arc Furnas EAF can cause an increase in grid voltage. In the other hand, the high-currents in power lines or a short-circuit in the grid can cause voltage dpis with a sudden decrease of the nominal voltage value which varies between 10% and 90% during a time betwen 10 to 1000 ms [6].

The effects of the voltage fault on a wind turbine are multiple; one of them is the dysfunction and the disconnection of the turbine with the wind turbine system.

In the other side, the electromechanical converter (DFIG in our case) may be sensible to voltage fault, especially if we know that during a voltage fault even if relatively low, stator current increases because of the direct coupling betwen the grid and the stator of the machine.

The fault current will pass through the rotor and the power converter causing a rotor over-current and an increase in the DC bus voltage [6].

In order to protect the rotor converter against the effect of the voltage fault, it’s necessary to use the active circuit voltage limiting such as Crowbar resistance and DC Shopper.

3. Active Disturbance Rejection Control

The parameters of the majority of physicals systems are subject to frequent variation, consequently, the conventional controllers are less efficient and less robust. Today, modern controllers are based on the estimation of perturbations through observers.

It is within this context that the ADRC proposes real-time estimation and cancellation of various internal or external perturbations using an Extended State Observer (ESO) [1]-[2]- [7] - [12].

This type of observers allows to estimate the external perturbations and also the internal dynamics of the system.

3.1. ADRC for Linear System

In general, for a system of n order, which can be written in the form:

$$y(t)^{(t)} = f(y(t)^{(n-1)}, y(t)^{(n-2)}, ..., y(t), d(t)) + bu(t) \tag{1}$$

Where:
f: Dynamic unknown parameter of the system
d: disturbance
b: Constant parameter
u : control law
For the estimation of the total disturbances, the control law adopted for this system is:

$$u = \frac{-f + u_0}{b} \tag{2}$$

In this case, the equation (1) can be written as follows

$$y^{(n)} = \frac{\widehat{f} + u_0}{b} \approx u_0 \tag{3}$$

In a first-order system, the equation (1) becomes:

$$\dot{y} = (y, d, t) + b_0 u \tag{4}$$

The ESO equation is written in matrix form as shown below:

$$\dot{X} = AX + Bu + Eh \tag{5}$$

Where:

$$A = \begin{bmatrix} 0 & 1 & \dots & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \dots & 1 \\ 0 & 0 & \dots & 0 \end{bmatrix}_{(n+1)\times(n+1)}, B = \begin{bmatrix} 0 \\ \vdots \\ b \\ 0 \end{bmatrix}_{(n+1)} \quad and \;\; E = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}_{(n+1)} \tag{6}$$

The extended state observer ESO established for equation (4) as:

$$\begin{cases} \dot{Z} = AZ + Bu + G(y - \widehat{y}) \\ \widehat{y} = CZ \end{cases} \tag{7}$$

With:

$$Z^T = \begin{bmatrix} z_1 \; z_2 ... \; z_{n+1} \end{bmatrix}, G^T = \begin{bmatrix} g_1 \; g_2 \; ... g_{n+1} \end{bmatrix}, C = \begin{bmatrix} 1 \; 0 \; ...0 \end{bmatrix} \tag{8}$$

To determine the parameters of G, we have:

$$g_n = \omega_0{}^n \beta_n \tag{9}$$

For a first-order system, we write the equation of the linear extended state observer ESO in the form:

$$\begin{cases} \dot{z} = Az + b_0 Bu + G(y - \widehat{y}) \\ \widehat{y} = Cz \end{cases} \tag{10}$$

With:

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}; B = \begin{bmatrix} 1 \\ 0 \end{bmatrix}; C^T = \begin{bmatrix} 1 \\ 0 \end{bmatrix}; G = \begin{bmatrix} 2\omega_0 \\ \omega_0{}^2 \end{bmatrix} \tag{11}$$

The control law is written:

$$u = \frac{u_0 - z_2}{b_0} \tag{12}$$

The system described in the equation (4) is then reduced to a simple integrator easily controllable by a proportional corrector kp.

$$\dot{y} = (f - z_2) + u_0 \approx u_0 \tag{13}$$

With:

$$u_0 = k_p(Y_{ref} - z_1) \qquad and \qquad k_p = \omega_c \tag{14}$$

Where Yref is the entry reference to follow and ω_0 is an observer bandwidth for ESO.

3.2. ADRC for Non Linear System

For the non-linear structures, the state observer equation is written as [8]:

$$\begin{cases} \dot{z} = z_2 - a_1 fal(e, \alpha_1, \delta_1) b_0 u \\ \dot{z}_2 = a_2 fal(e, \alpha_2, \delta_2) \\ e = z_1 - y \end{cases} \tag{15}$$

With:

fal: is a nonlinear function developed by Jingqing Han [11] such as:

$$fal(e, \alpha, \delta) = \begin{cases} |e|^{\alpha} sign(e) \ \ if \ \ |e| \geq \delta \\ \dfrac{e}{\delta^{1-\alpha}} \qquad if \ \ |e| \prec \delta \end{cases} \tag{16}$$

The control law is given by:

$$u_0 = k_p fal(Y_{ref} - z_1, \alpha, \delta) \tag{17}$$

With:

α is to be adjusted and which value is between 0 and 1 [10].

δ is inferior to 1.

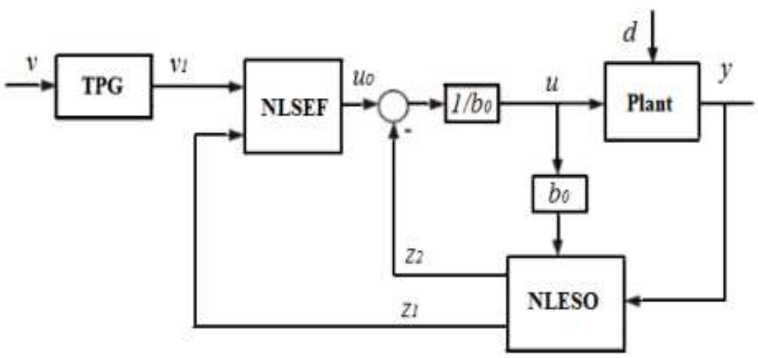

Figure 2. Architecture of ADRC Controller

3.3. ADRC for WECS Control

Pitch angle control:

The pitch angle is controlled so that the Wind Energy Conversion System (WECS) operates in its safe region and to extract the maximum electrical power from the turbine. We consider the following equation:

$$\frac{d\Omega_m}{dt} = \frac{1}{J}(T_g - T_{em} - f\Omega_m) \tag{18}$$

This equation can be written in the ADRC canonical form as below:

$$\frac{d\Omega_m}{dt} = f(\Omega_m, d, t) b_0 \beta \tag{19}$$

Where:

$f.\Omega_m$:Viscous friction torque
$T_{em:}$ Electromagnetic torque
β : Pitch angle
T_g :Generator torque
Ω_m:Mechanical speed

RSC control

In our study, the decoupling between the active Ps and reactive power Qs is done by the orientation of the quadratic component of the statoric voltage Vsq on the q-axis [1]. In this condition we will have:

$$\begin{cases} V_{ds} = 0 \\ V_{qs} = V_s = \omega_s \Phi_{ds} \end{cases} \tag{20}$$

In the d-q reference frame, the DFIG power can be written as:

$$\begin{cases} P_s = V_{qs} I_{qs} + V_{ds} I_{ds} = -V_s \frac{L_m}{L_s} I_{qr} \\ Q_s = V_{qs} I_{ds} - V_{ds} I_{qs} = V_s (\frac{\Phi_s}{L_s}) - V_s (\frac{L_m}{L_s}) I_{dr} \end{cases} \tag{21}$$

The rotor's voltages are given by:

$$\begin{cases} V_{dr} = R_r I_{dr} + \sigma L_r \frac{dI_{dr}}{dt} - g\omega_s \sigma L_r I_{qr} \\ V_{qr} = R_r I_{qr} + \sigma L_r \frac{dI_{qr}}{dt} - g\omega_s \sigma L_r I_{dr} + g(\frac{L_m V_s}{L_s}) \end{cases} \tag{22}$$

We can establish the expression of the currents from the equation (22):

$$\begin{cases} \frac{dI_{dr}}{dt} = \frac{V_{dr}}{\sigma L_r} - \frac{R_r I_{dr}}{\sigma L_r} + g\omega_s I_{qr} \\ \frac{dI_{qr}}{dt} = \frac{V_{qr}}{\sigma L_r} - \frac{R_r I_{qr}}{\sigma L_r} + g\omega_s I_{dr} - g(\frac{L_m V_s}{\sigma L_r L_s}) \end{cases} \tag{23}$$

With:

Vds, Vqs : Direct and quadratic stator voltages

Vdr, Vqr: Direct and quadratic rotor voltages

Ids, Iqs: Direct and quadratic stator currents

Idr, Iqr: Direct and quadratic rotor currents

Φ_{ds} ,Φ_{qs}: Direct , quadratic stator flux

ωs, ωr : Synchronous and Angular speed

The ADRC canonical form of this equation can be written as:

$$\begin{cases} \frac{dI_{dr}}{dt} = f_d(I_{dr}, d, t) + b_0 u_d(t) \\ \frac{dI_{qr}}{dt} = f_q(I_{qr}, d, t) + b_0 u_q(t) \end{cases} \tag{24}$$

DC bus voltage Control:

According to the power balance of the chain, we have:

$$\begin{cases} P_{dc} = u_{dc} i_{dc} = \frac{3}{2} V_{qs} I_{qf} \\ P_{rsc} = u_{dc} i_{rsc} = -P_r \\ P_{gsc} = u_{dc} i_{gsc} = -P_g \end{cases} \tag{25}$$

We then obtain:

$$c u_{dc} \frac{du_{dc}}{dt} = P_{rsc} - P_{gsc} \tag{26}$$

With:

I_{fq} :The current in the filter in q axis
I_{gsc}: The output current of the rectifier
I_{rsc} :The input current of the inverter

If we neglect the power lost in the filter and the electronic switches supposed ideal, we have:

$$c u_{dc} \frac{du_{dc}}{dt} = \frac{3}{2} V_{qs} I_{qf} - u_{dc} i_{rsc} \tag{27}$$

In this equation, Irsc is considered as a load current for the RSC.

To simplify the previous equation in canonical form of the ADRC we put $\omega = Udc^2$:

$$\frac{dw}{dt} = f(\omega, d, t) + b_0 u \tag{28}$$

Filter current control:

The objective of the control is to ensure a desired Power Factor, PF=1 and to manage the transmission of the rotor power with and without defect, in the d-q axis the filter current equation are given by:

$$\begin{cases} L_f \frac{dI_{df}}{dt} + R_f I_{df} + L_f \omega_s i_{qf} = V_{ds} - V_{df} \\ L_f \frac{dI_{qf}}{dt} + R_f I_{qf} + L_f \omega_s i_{df} = V_{qs} - V_{qf} \end{cases} \tag{29}$$

The equation of current in the filter in the canonical form of the ADRC is given by:

$$\begin{cases} \frac{dI_{df}}{dt} = f(I_{df}, d, t) + b_0 u(t) \\ \frac{dI_{qf}}{dt} = f(I_{qf}, d, t) + b_0 u(t) \end{cases} \tag{30}$$

3.4. Control During Voltage Fault:

In case of voltage dpis, the high-current saturates the magnetization inductance; the reactive power is absorbed from the grid for the magnetization of the DFIG. As result, the grid voltage will be more and more distributed.

The purpose of the control is to avoid the trip of the circuit of the DFIG during voltage dips regardless of the type of the fault. It done by limiting the fault current and increasing the DC bus voltage. The flux to the stator is deprived because the stator is directly connected to the network.

However, the quadrature component of the flux is no longer zero and the value of the roper of the park is modified. Under these conditions the statoric and rotoric voltages will be:

$$V_{ds} = \frac{R_s}{L_s}\Phi_{ds} + \frac{d\Phi_{ds}}{dt} - R_s\frac{L_m}{L_s}I_{dr} - \omega_s\Phi_{qs} \tag{31}$$

$$V_{qs} = \frac{R_s}{L_s}\Phi_{qs} + \frac{d\Phi_{qs}}{dt} - R_s\frac{L_m}{L_s}I_{qr} + \omega_s\Phi_{ds} \tag{32}$$

$$V_{dr} = R_r I_{dr} + \sigma L_r\frac{dI_{dr}}{dt} - \sigma\omega_r L_r I_{qr} - \omega_r\frac{L_m}{L_s}\Phi_{qs} + \frac{L_m}{L_s}\frac{d\Phi_{ds}}{dt} \tag{33}$$

$$V_{qr} = R_r I_{qr} + \sigma L_r\frac{dI_{qr}}{dt} + \sigma\omega_r L_r I_{dr} + \omega_r\frac{L_m}{L_s}\Phi_{ds} + \frac{L_m}{L_s}\frac{d\Phi_{qs}}{dt} \tag{34}$$

From the equation 33 and 34, we get the following expression for rotor's currents:

$$\begin{cases} \dfrac{di_{dr}}{dt} = -\dfrac{R_r}{\sigma L_r}I_{dr} + \omega_r I_{qr} + \omega_r\dfrac{L_m}{\sigma L_r L_s}\Phi_{qs} \\ -\dfrac{L_m}{\sigma L_r L_s}\dfrac{d\Phi_{ds}}{dt} + \dfrac{1}{\sigma L_r}V_{dr} \\ \dfrac{di_{qr}}{dt} = -\dfrac{R_r}{\sigma L_r}I_{qr} - \omega_r I_{dr} - \omega_r\dfrac{L_m}{\sigma L_r L_s}\Phi_{ds} \\ -\dfrac{L_m}{\sigma L_r L_s}\dfrac{d\Phi_{qs}}{dt} + \dfrac{1}{\sigma L_r}V_{qr} \end{cases} \tag{35}$$

This equation can dimension the corrector ADRC. To do this, we can put the equation 35 in the ADRC canonical form:

$$\begin{cases} \dfrac{di_{dr}}{dt} = f_{dr}(i_{dr}, d, t) + b_0 u_{dr}(t) \\ \dfrac{di_{qr}}{dt} = f_{qr}(i_{qr}, d, t) + b_0 u_{qr}(t) \end{cases} \tag{36}$$

With:

$$\begin{cases} f_{dr} = -\dfrac{R_r}{\sigma L_r}I_{dr} + \omega_r I_{qr} + \omega_r\dfrac{L_m}{\sigma L_r L_s}\Phi_{qs} \\ -\dfrac{L_m}{\sigma L_r L_s}\dfrac{d\Phi_{ds}}{dt} + (\dfrac{1}{\sigma L_r} - b_0)V_{dr} \\ f_{qr} = -\dfrac{R_r}{\sigma L_r}I_{qr} - \omega_r I_{dr} - \omega_r\dfrac{L_m}{\sigma L_r L_s}\Phi_{ds} \\ -\dfrac{L_m}{\sigma L_r L_s}\dfrac{d\Phi_{qs}}{dt} + (\dfrac{1}{\sigma L_r} - b_0)V_{qr} \end{cases} \tag{37}$$

And

$$\begin{cases} u_{dr} = V_{dr} \\ u_{qr} = V_{qr} \\ b_0 = -1/\sigma L_r \end{cases} \tag{38}$$

4. Simulation Results

In order to study the ADRC performance applied to the DFIG during the voltage grid fault, two faults have been simulated successfully:

Fault A: Overvoltage of 15% for 500ms.
Fault B: Undervoltage of 80% for 300ms.

The both faults A and B are shown in figure N°4, as we can see the voltage nominal value increase between 1 second and 1.5 second, and decrease from the instant t=2.5s to t=2.8s.

The simulations of the complete wind conversion chain with the Crowbar resistors and the DC SHOPPER are performed by MATLAB Simulink, the parameters of the studied ADRC and DFIG are given in the appendix.

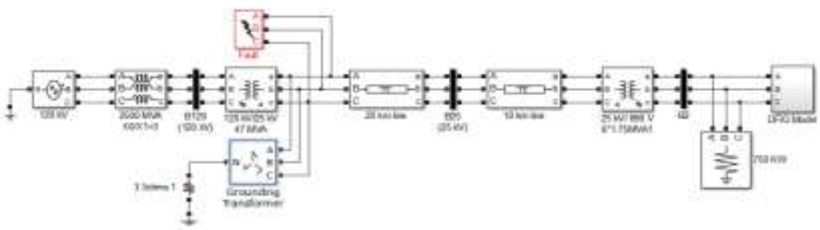

Figure 3. The Simulated System

In this simulation we tried to introduce all the elements constituting an electrical network connected with a turbine and supplying a resistive load, in fact our system consists of a wind turbine of 1.5MW connected to a 120Kv electrical network through two power transformers, 25 / 0.690kv and 25/125kV - 47MVA transformer, the electrical energy generated will carry two lines; 10Km and 20Km. A resistive load of 750Kw is connected to the turbine.

As shown in the following figure, under voltage fault is monitored on the 20Km line, overvoltage fault happened when the load is disconnected.

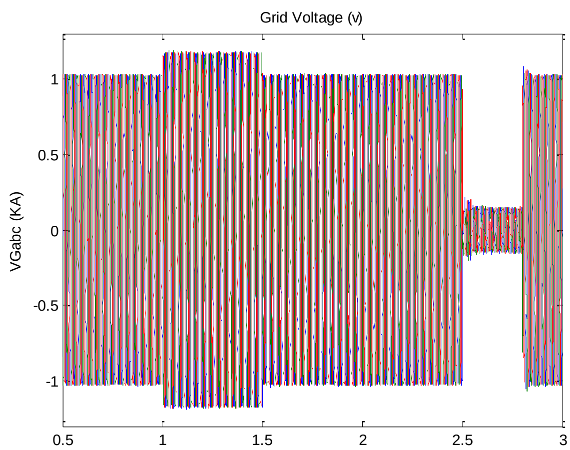

Figure 4. Grid Voltage (pu) 15% Overvoltage and with 85% Undervoltage

To analyze the performance of the ADRC in case of voltage fault (undervoltage and overvoltage) the DFIG is connected to the grid with a perturbed voltage in two times as shows the previous figure:

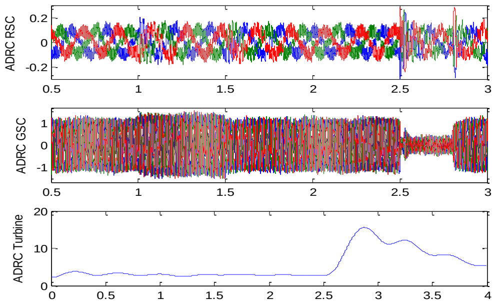

Figure 5. Control Law Generated by the ADRC Bloc for RSC Converter, GSC Converter and Turbine

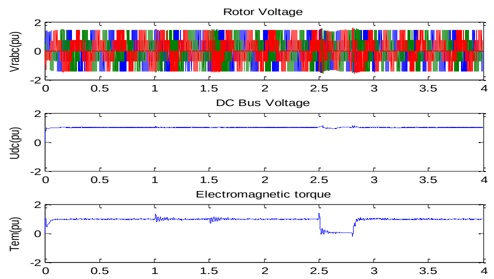

Figure 6. Signals Controlled by ADRC: Rotor Voltage Vrabc, dc Link Voltage Udc and Electromagnetic Torque Tem

5. Results Interpretation

From the results we can conclude that the ADRC ensure the high performance for DFIG power control during the voltage grid fault, as we can see in the figure 7, the statoric active power is kept constant during overvoltage grid fault with a little perturbation around 18% at t=1s and 13% at t=1.5s. But the ADRC effect returns the power to its nominal value in 0.3s during the under voltage fault. In the other side this power drops nearly to zero in case of undervolatge grid fault.

At the instant t=2.5s, the grid absorbs reactive power from DFIG under effect of grid voltage fault and therefore the value of the power factor changes.

The presence of a voltage limiter circuit keeps the rotor side converter connected and ensures the control of the reactive power exchanged between the generator and the grid.

The adopted ADRC control law for turbine increases significantly under voltage fault, hence the rapid increase in the speed of rotation of the generator. As result, the pitch angle β changes in order to keep the rotor speed at the rated value.

The signal for GSC control generated by the ADRC bloc is calculated from the network characteristics which gives a form similar to the grid voltage.

From Figure 5, we can conclude that the DC bus voltage Udc keeps his constant value with a little perturbation during voltage fault, but the effect of ARDC maintain this perturbation under acceptable value.

The evolution of the electromagnetic torque is shown in Figure 5, it drops nearly to zero and keeps constant during grid under voltage, as a result the supplied power dropped significantly.

At the end of this discussion, we note that the parameters of the used ADRC for turbine, GSC and RSC are determined by simulation and are listed in Table 2 of the appendix.

6. Conclusions

This paper investigated the performances of ADRC during grid voltage fault such as overvoltage and undervoltage, the ADRC synthesize and control strategy has been clearly developed. In both overvoltage and undervoltage voltage fault, the DFIG still connected to the grid and extchange the power without losing power converter control.

The simulation results show the high performance of ADRC in case of grid voltage fault. In the same way, many articles have evaluated the performance of the ADRC in case of DFIG parameter variation.

In this article, we are not interrested in the frequency behaviour and it will be the topic of our next work research.

Appendix

Table 1. DFIG Parameters

Parameter name	Symbol	Value	Unit
Rated power	P	1.5	MW
Statoric voltage	Vs	690 – 50	V- Hz
Rotoric voltage	Vr	389 - 14	V- Hz
Statoric resistance	Rs	0.012	Ω
Rotoric resistance	Rr	0.021	Ω
Statoric inductance	Ls	0.0137	H
Rotoric inductance	Lr	0.0136	H
mutual inductance	Lm	0.0135	H
Pole pairs	P	2	
The friction Coefficient	F	0.024	N.m.s-1
The moment of inertia	J	1000	kg.m2

Table 2. ADRC Parameters

ADRC Parameters	Turbine	RSC	GSC
kp	7.5	130	60
b0	0.04	253	810
α	0.85	0.25	0.9
β	0.0001	0.001	0.001
Wc	100	150	60
W0	300	400	200

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