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Active Disturbance Rejection Control of Doubly-Fed Induction Generator during Voltage Dip

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Abstract— **This paper presents the Simulink modeling of the doubly-fed induction generator (DFIG) and the implementation of the active disturbance rejection controller (ADRC) to control the rotor current. The generator is required to remain connected to the grid during the fault ride-through period and at the same time the rotor side converter need to be protected from consequent over-current and destruction. The proposed control strategy is activated when the limit of the rotor current is violated due to the terminal voltage sagging usually caused by the fault on the electrical grid. The dynamic model of the DFIG was developed with Simulink and two ADRC controllers were implemented for the rotor current in dq frame. The Extended State Observer (ESO), the basic element of ADRC, estimates disturbance in real-time while the disturbance (internal and external) is compensated via control law. The preliminary simulation results show strong evidence of the effectiveness of the ADRC although further system parameter tuning is needed to achieve optimum performance.**

I. Introduction

Wind energy is green and pollution-free. It was estimated in the latest study of National Renewable Energy Laboratory (NREL) that up to 30% of the electricity will come from wind by 2024 [1]. Wind energy technology has evolved rapidly over the past three decades with increasing rotor diameters and the use of sophisticated power electronics to allow operation at variable speed [2]. Doubly Fed Induction Generator (DFIG) is one of the most popular variable speed wind turbines in use nowadays. As shown in Fig. 1, its stator is connected to the grid through transformers while its rotor is connected to the grid via two back-to-back voltage source inverters (VSIs). By controlling the level and phase of the injected voltage to the rotor windings, variable speed operation can be realized to extract the maximum power from the wind. During the voltage sag due to a nearby grid fault, the rotor current will increase and the speed of the turbine increases as well. If the voltage can not be recovered soon enough, in order to protect the wind turbine, it should be tripped off from the grid. But as the penetration level of the wind energy into the power grid gets higher, the series of tripping off a large capacity of the wind turbines (wind farms) may occur and cause a consequent grid collapse or even blackout. Therefore, the fault ride-through capability of the wind turbine with large capacity becomes critical for the stability of the power system. This means, the wind turbine is required to remain connected to the grid in case of grid voltage sags for a period of time which depends on the severity of the voltage sag. The main concern is to protect the power electronics converters connected to the rotor which may be destructed due to thermal limit with overcurrent. Two popular approaches have been proposed to solve this problem. The first approach is to short circuit the rotor windings with crowbars [3]or to share part of the overcurrent with thyristor bypass resistors[4]. Another approach is to directly limit the rotor current by applying different control strategy [5][6][7][8][9] in the voltage sag and recovery period.

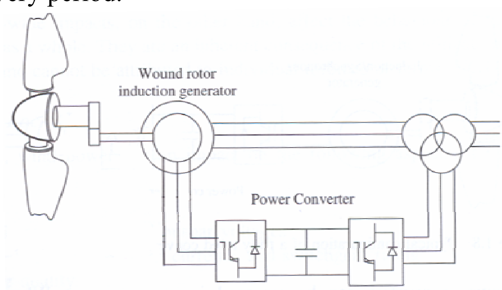


Fig. 1. typical configuration of DFIG[2]

This paper presents the preliminary research of adopting the active disturbance rejection control (ADRC) strategy to limit the rotor current during the voltage sag. The complete DFIG Simulink model and the implementation of the ADRC controller are presented. The predicted performance of the DFIG with and without the protection is presented and discussed. At current stage, the power electronics converters are assumed to be able to react to the control signal without any delay.

II. SIMULINK MODEL OF THE DFIG

The DFIG is a wound-rotor induction machine with injected voltage to the rotor windings. Different from a squirrel-cage induction machine which the rotor windings are short circuited, the DFIG has a three-phase voltage source in its rotor side. For the simplicity, a general induction machine model in d-q frame [10] was adopted and modified to model the DFIG under study. The modeling equations in flux linkage form are as follows:

$$\begin{cases} \dfrac{dF_{qs}}{dt} = \omega_b \left[v_{qs} - \dfrac{\omega_e}{\omega_b} F_{ds} + \dfrac{R_s}{x_{ls}} \left(F_{mq} + F_{qs} \right) \right] \\ \dfrac{dF_{ds}}{dt} = \omega_b \left[v_{ds} + \dfrac{\omega_e}{\omega_b} F_{qs} + \dfrac{R_s}{x_{ls}} \left(F_{md} + F_{ds} \right) \right] \end{cases} \quad (1)$$

$$\begin{cases} \dfrac{dF_{qr}}{dt} = \omega_b\left[v_{qr} - \dfrac{(\omega_e - \omega_r)}{\omega_b}F_{dr} + \dfrac{R_r}{x_{lr}}\left(F_{mq} - F_{qr}\right)\right] \\ \dfrac{dF_{dr}}{dt} = \omega_b\left[v_{dr} + \dfrac{(\omega_e - \omega_r)}{\omega_b}F_{qr} + \dfrac{R_r}{x_{lr}}\left(F_{md} - F_{dr}\right)\right] \end{cases} \quad (2)$$

$$\begin{cases} i_{qs} = \dfrac{1}{x_{ls}}(F_{qs} - F_{mq}) \\ i_{ds} = \dfrac{1}{x_{ls}}(F_{ds} - F_{md}) \\ i_{dr} = \dfrac{1}{x_{lr}}(F_{dr} - F_{md}) \\ i_{qr} = \dfrac{1}{x_{lr}}(F_{qr} - F_{mq}) \end{cases} \quad (3)$$

$$T_e = \frac{3p}{4}\frac{1}{\omega_b}(F_{ds}i_{qs} - F_{qs}i_{ds}) \quad (4)$$

$$T_e - T_l = J\frac{2}{P}\frac{d\omega_r}{dt} \quad (5)$$

where,
F – the flux linkage
T_e – electrical magnetic torque
T_l – load torque
ω_e – synchronous electrical angular speed
ω_b – base electrical angular speed
ω_r – rotor electrical angular speed
i – current in dq frame

The corresponding Simulink model representing equations (1) to (5) were shown in Fig. 2. The mechanical torque, the stator and rotor input voltages and the synchronous speed are the inputs and the electrical magnetic torque, the stator and rotor currents and the rotor speed are the outputs. Fig. 3 displays the completed DFIG Simulink model including three transforming blocks and the blocks for flux angle calculation. The block “abc-dq” transforms three-phase grid voltage to dq frame. The blocks “stator-abc” and “rotor-abc” transform the stator and rotor currents to dq frame to three-phase respectively. The inputs of the DFIG are the three-phase stator voltage, synchronous electric angular speed, load torque and the rotor injection voltages in dq frame. The outputs are three-phase stator current, three-phase rotor current, electrical magnetic torque, rotor speed and the rotor current in dq frame.

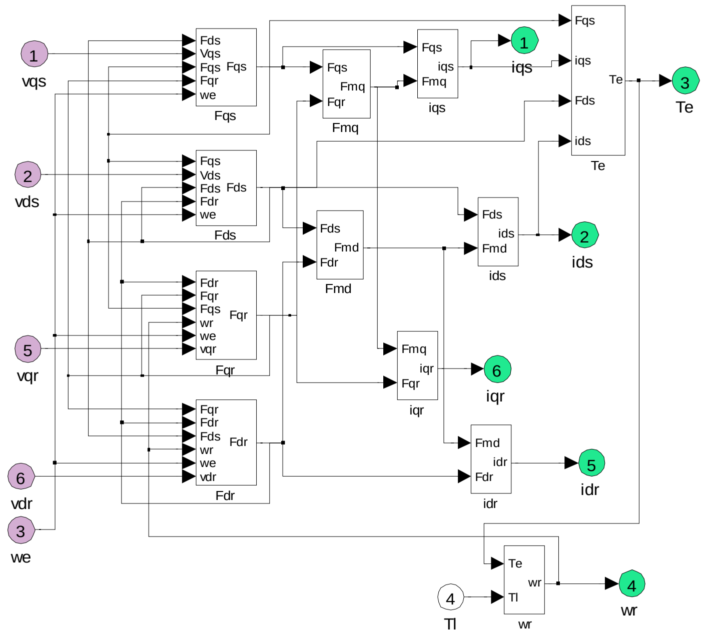


Fig. 2. DFIG dynamic model in d-q frame implementation in Simulink

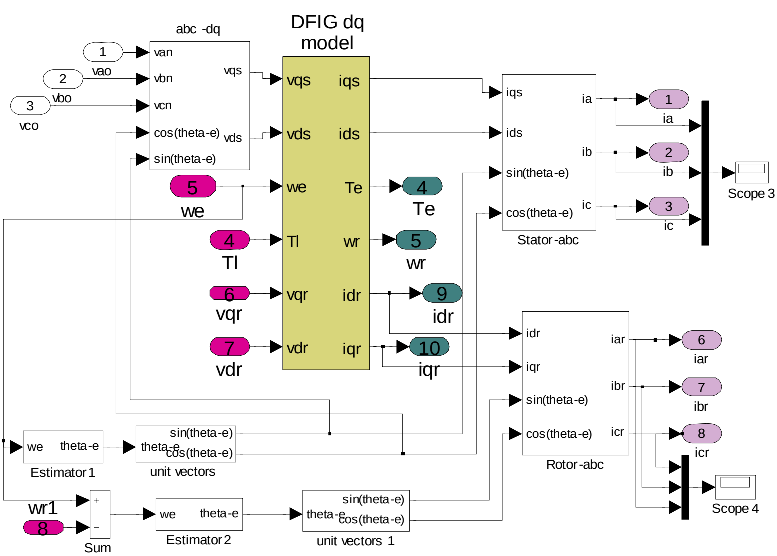


Fig. 3. the complete DFIG Simulink model

III. ADRC IMPLEMENTATION FOR ROTOR CURRENT CONTROL

The active disturbance rejection control (ADRC) [11] [12] was adopted to carry out the rotor current control. The brief description of the ADRC is as the following. For a second-order plant,

$$\ddot{y} = f(t, y, \dot{y}, w) + bu \quad (6)$$

with $x_3 = f$ as an augmented state, its state space form is,

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u + \mathbf{E}h \\ y = \mathbf{C}\mathbf{x} \end{cases} \quad (7)$$

where *y* is output to be controlled, *u* the input, *w* the disturbance, A=[0 1 0; 0 0 1; 0 0 0], B=[0; b_0; 0], E=[0; 0; 1], C=[1 0 0], and $h = \dot{f}$.

Let $z_1, z_2, and\ z_3$ be the estimates of $y,\ \dot{y},\ and\ f$ respectively, the extended state observer corresponding to (14) can be written as

$$\begin{cases} \dot{\mathbf{z}} = \mathbf{A}\mathbf{z} + \mathbf{B}u + \mathbf{L}(y - \hat{y}) \\ \hat{y} = \mathbf{C}\mathbf{z} \end{cases} \quad (8)$$

If the observer can track the system dynamic states fast enough, the error of the estimation can be ignored. This perfectly tuned observer leads to $z_3 \cong f$. Then with the control law

$$u = (u_0 - z_3)/b_0 \quad (9)$$

the plant given by (6) reduces to a double integral plant $\ddot{y} = u_0$ which can be easily controlled with PD controller [12],

$$u_0 = k_p(r - z_1) - k_d z_2 \quad (10)$$

where *r* is the reference input, and k_p and k_d are the PD gains respectively.

Fig. 4 gives the implementation information of the ADRC for i_{qr} with the ADRC controller noted as inside the dished block. A similar controller can be applied to i_{dr}.

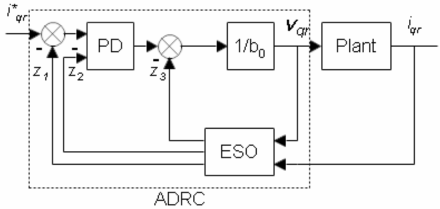


Fig. 4. ADRC controller for i_{qr}

IV. PRELIMINARY SIMULATION RESULTS

Two controllers have been implemented for i_{dr} and i_{qr} respectively as shown in Fig. 5. The current-mode control technique is used to control the rotor-side converter by generating the PWM three-phase control voltage, and eventually to generate the required rotor-side injection voltage. The rotor current is split into two orthogonal components, d and q as shown in Fig. 2. The q component of the current i_{qr} is used to regulate the torque and the d component i_{dr} is used to regulate the terminal voltage [2]. But when there is voltage sag sensed, the prior sag values of i_{qr}^{*} and i_{dr}^{*} will be used as the reference inputs to the controller till the end of the fault-ride-through and the recovery period.

Simulation was carried out to verify the effectiveness of the controller with the assumption of the terminal voltage having a 50% voltage dip at 2s. The fault lasts for 200ms and recovers back to normal as shown in Fig. 6 (a). The rotor speed response was displayed in Fig. 6 (b) which clearly shows the speed fluctuation and increasing during the voltage sag.

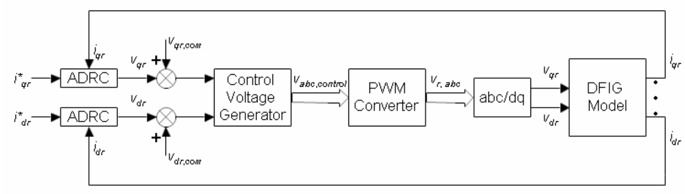
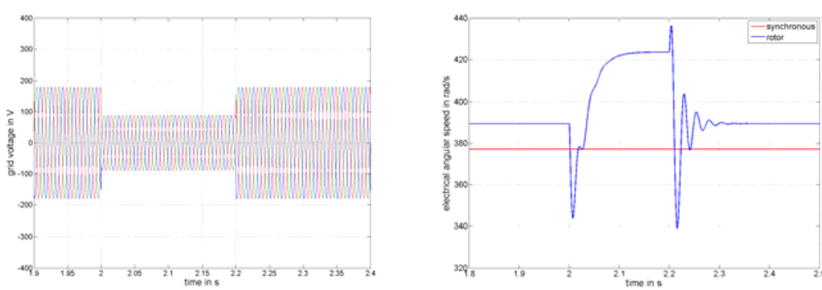


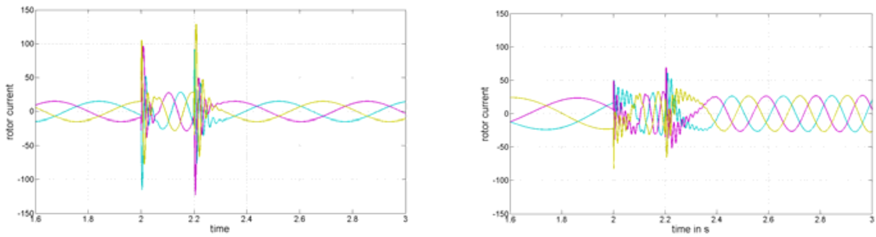
Fig. 5. control loops for rotor current with two ADRC controllers



(a) (b)

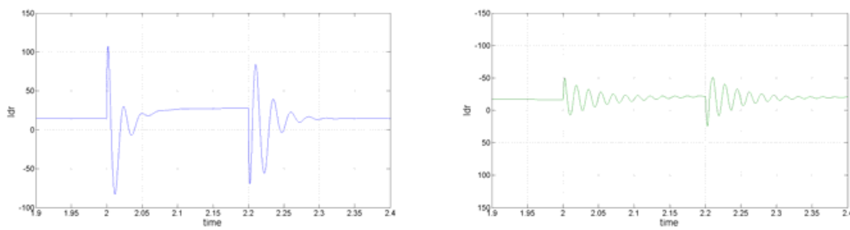
Fig. 6 (a) terminal voltage shown the sagging and (b) the corresponding rotor speed

Fig. 7 (a) displays the corresponding three-phase rotor current during the 200ms voltage sag without the current protection. Large spikes were evidenced. Fig. 7 (b) shows the simulation results of the rotor side current with the ADRC controller in place. Although current fluctuation still seems relatively big, the current magnitude has been kept in a reasonable range. The relatively higher frequency after voltage recovery is due to the deactivation of the speed loop control. Fig. 8 (a) and (b) show the rotor current from another perspective, in dq frame. Fig. 8(a) is corresponding to the three-phase in Fig. 7 (a) while Fig. 8 (b) to Fig. 7 (b).



(a) (b)

Fig. 7 three-phase rotor current (a) without and (b) with the current protection control during a voltage dip



(a) (b)

Fig. 8 rotor current i_{dr} (a) without and (b) with the current protection control during a voltage dip

V. Discussions

The Simulink model of the doubly-fed induction generator (DFIG) was developed and two ADRC controllers were implemented to control the rotor current. The preliminary simulation results provide the evidence of the effectiveness of the ADRC to keep the rotor current under certain limitation. On the other hand, the results also revealed relatively large fluctuation and room for improvement. As a requirement of the ADRC control technique, the controller parameters need to be fine tuned in order to optimum performance. The future work also includes continuous monitoring and realizing variable speed control of the DFIG and the consideration of the practical issues of the power electronics converters in the Simulink model.

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