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Fuzzy Logic Control of Doubly Fed Induction Generator Wind Turbine

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Abstract: This paper presents fuzzy logic control of Doubly Fed Induction Generator (DFIG) wind turbine in a sample power system. DFIG consists of a common induction generator with slip ring and a partial scale power electronic converter. Fuzzy logic controller is applied to rotor side converter for active power control and voltage regulation of wind turbine. Wind turbine and its control unit are described in details. All power system components are simulated in PSCAD/EMTDC software and for fuzzy control, using a user defined block, this software is linked to MATLAB. For studying the performance of controller, different abnormal conditions are applied even the worst case. Simulation results prove the excellent performance of fuzzy control unit as improving power quality and stability of wind turbine.

Key words: Wind Turbine . doubly fed induction generator . fuzzy logic control

INTRODUCTION

Wind energy is one of the extra ordinary sources of renewable energy due to its clean character and free availability. Moreover, because of reducing the cost and improving techniques, the growth of wind energy in Distributed Generation (DG) units has developed rapidly

In terms of wind power generation technology, because of numerous technical benefits (higher energy yield, reducing power fluctuations and improving var supply) the modern MW-size wind turbines always use variable speed operation which is achieved by a converter system [1]. These converters are typically associated with individual generators and they contribute significantly to the costs of wind turbines. Between variable speed wind turbine generators, doubly fed induction generators (DFIGs) and permanent magnet synchronous generators (PMSGs) with primary converters, are emerging as the preferred technologies [2].

Doubly fed induction generator (DFIG) is one of the most popular wind turbines which includes an induction generator with slip ring, a partial scale power electronic converter and a common DC-link capacitor. Power electronic converter which encompasses a back to back AC-DC-AC voltage source converter has two main parts; grid side converter (GSC) that rectifies grid voltage and rotor side converter (RSC) which feeds rotor circuit. Power converter only processes slip power therefore it's designed in partial scale and just about 30% of generator rated power [3] which makes it attractive from economical point of view.

Many different structure and control algorithm can be used for control of power converter. One of the most common control techniques is decouple PI control of output active and reactive power to improve dynamic behavior of wind turbine. But due to uncertainty about the exact model and behavior of some parameters such as wind, wind turbine, etc and also parameters values differences during operation because of temperature, events or unpredictable wind speed, tuning of PI parameters is one of the main problems in this control method.

Using fuzzy control, we can produce controller outputs more reliable because the effect of other parameters such as noise and events due to wide range of control region and online changing of the controller parameters can be considered. More over without the need of a detailed mathematical model of the system and just using the knowledge of the total operation and behavior of system, tuning of parameters can be done more easily.

This paper investigates dynamic modeling of a variable speed DFIG wind turbine using fuzzy controller in PSCAD/EMTDC software. Different parameters in normal and abnormal conditions based on fuzzy control are studied. A main grid with two different distribution generator, a 5MVA common synchronous generator and a 2MVA DFIG wind turbine are used and focuses turned to fuzzy control unit and its effects on the power quality and system response of

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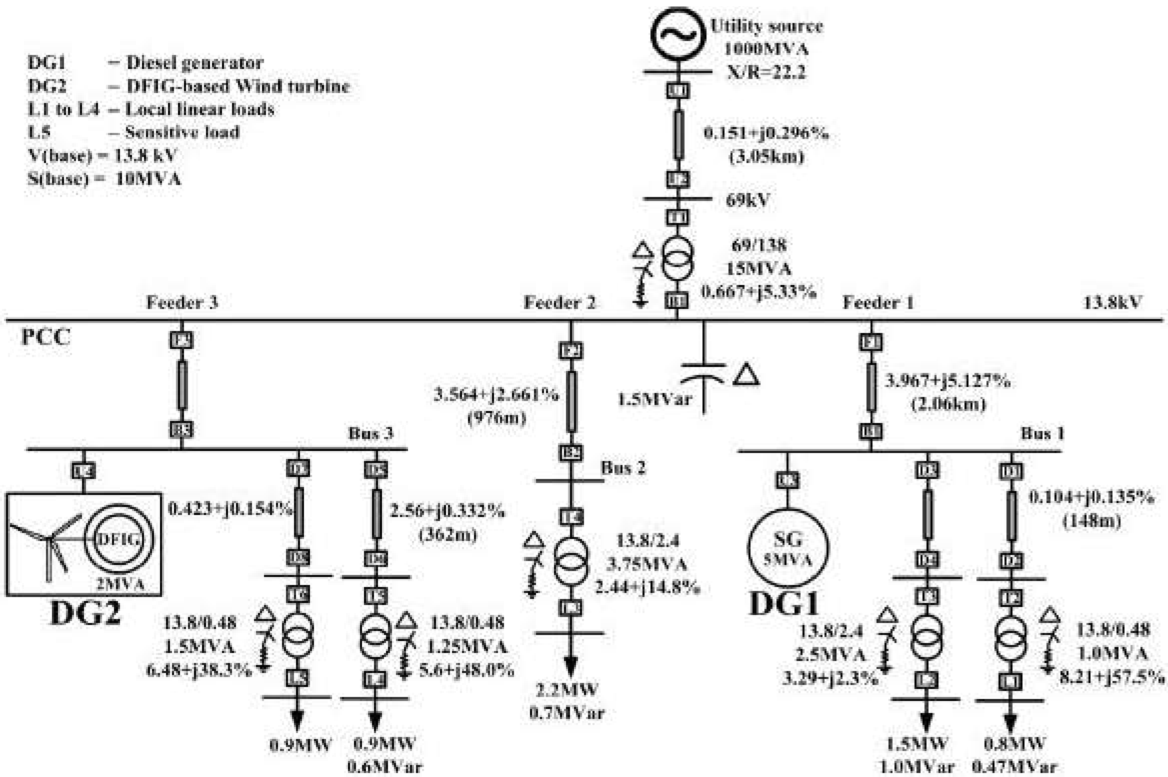


Fig. 1: Single line diagram of study system

DFIG. In this study induction machine and electrical components such as transformer, capacitor banks, etc are used from standard components of a dedicated power system analysis tool PSCAD/EMTDC, but other parts are modeled from user defined models by assembling them visually using existing models and utilizing an intuitively graphical design editor and writing codes in Fortran [4]. For fuzzy controller, PSACD/EMTDC linked to MATLAB and in the process both software work simultaneously therefore MATLAB calculates fuzzy controller outputs and transmits them to PSCAD/EMTDC environment in any step simulation time.

STUDY SYSTEM

Figure 1 represents single line diagram of studied system in this paper. Configurations and parameters of the system are extracted from [5] with a little change in local load values. Micro-grid consists of three main feeders, two DG units and five local loads. Main grid is represented by a three phase 69 kV voltage source with 1000MVA short circuit capacity and X/R ratio of 22.2. Micro-grid is normally connected to the main grid through a 15MVA upward transformer.

L1 to L4 are local linear loads and L5 is a nonlinear load which is presented thorough a three phase diode rectifier that feeds a resistance as a resistive load

Connection point of main and micro-grid which is called Point of Common Coupling (PCC) is fed through a 1.5 Mvar fixed shunt capacitor bank.

DG1 is a 5MVA synchronous generator with its exciter and governor system. It can be considered as a diesel or gas turbine generator unit. It's connected directly to bus 1 and thorough a 2.06Km radial line to the PCC. Its parameters are described in Table 1.

DG2 is a 2MVA doubly fed induction generator (DFIG) wind turbine which consists of an asynchronous generator with power electronic converter control unit which feeds generator's rotor and wind turbine as prime mover. Power electronic converter unit is to control active and reactive power of generator separately and to improve power quality and stability of the network.

Table 1: Synchronous generator (DG1) parameters

Rated power	5 MVA	Rated voltage	13.8 kV
Ra	0.0052 p.u	X_{ls}	0.2 p.u
X_d	2.86 p.u	X_q	2.0 p.u
X_d'	0.7 p.u	X_q'	0.85 p.u
X_d''	0.22 p.u	X_q''	0.2 p.u
T_{do}'	3.4 s	T_{qo}''	0.05 s
T_{do}''	0.01 s	H	2.9 s

WIND AND WIND TURBINE MODEL

Wind effect plays a fundamental rule in wind turbine modeling especially for interaction analysis between wind turbines and the power system to witch they are connected. Wind model describes wind fluctuation in wind speed which causes power fluctuation in generator. For wind model four components can be considered, as describe in (1) [6]:

$$V_{wind} = V_{bw} + V_{gw} + V_{rw} + V_{nw} \quad (1)$$

Where,
V_{bw} = Base wind component (*m/s*);
V_{gw} = Gust wind component (*m/s*);
V_{rw} = Ramp wind component (*m/s*);
V_{nw} = Noise wind component (*m/s*).

The base component is a constant speed; wind gust component may be expressed as a sine or cosine wave function or their combination [7]; a simple ramp function will be used for ramp component and a triangle wave for noise function which it's frequency and amplitude will be accordingly adjusted. Wind speed in this study is illustrated in Fig. 9 and includes all of four components.

For electrical analysis, a simplified aerodynamic model of wind turbine is normally used. Accordingly wind blade torque from wind speed will be produced which is as follows:

$$\lambda = \frac{R\omega_{rot}}{V_{wind}} \quad (2)$$

$$P_w = \frac{1}{2}\rho\pi R^2 C_p(\lambda,\theta)V_{wind}^3 \quad (3)$$

$$T_w = \frac{P_w}{\omega_{rot}} = \frac{\rho\pi R^3 C_p(\lambda,\theta)V_{wind}^2}{2\lambda} \quad (4)$$

Where T_w is an aerodynamic torque extracted from the wind (*Nm*), ρ is the air density (*kg/m*^{3}), R is the wind turbine rotor radius (*m*), V_{wind} is the equivalent wind speed (m/s), θ is the pitch angle of the rotor (*deg*), λ is the tip speed ratio, ω_{rot} is the mechanical speed of the generator (*rad/s*) and C_p is the power coefficient.

C_p can be expressed as a function of the Tip Speed Ratio (TSR) and pitch angle which is given by (5) [8], [9]:

$$\begin{cases} C_p(\lambda,\theta) = 0.22\left(\frac{116}{\lambda_i} - 0.4\theta - 5\right)e^{\frac{-12.5}{\lambda_i}} \\ \lambda_i = \frac{1}{\left(\frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1}\right)} \end{cases} \quad (5)$$

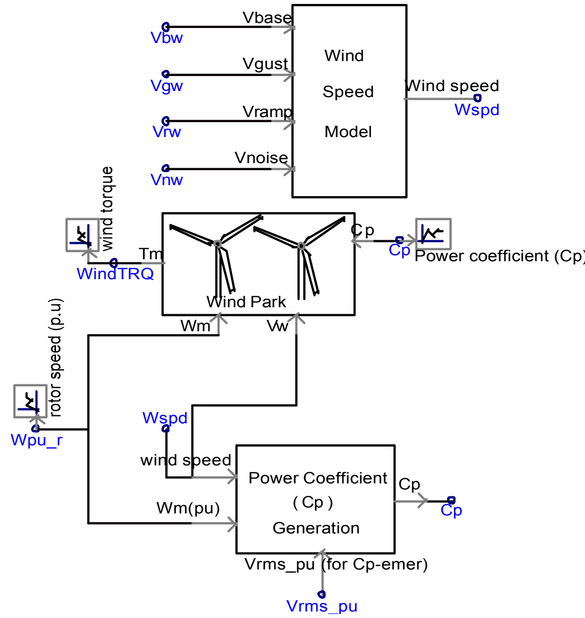


Fig. 2: Wind speed and power coefficient modeled in PSCAD/EMTDC

By increasing pitch angle, power coefficient and therefore torque decreases moreover C_p growth rate changes in different speed by λ. Wind speed and power coefficient production are shown in Fig. 2.

DFIG MODEL

As illustrated in Fig. 3, DFIG system is a wound rotor induction generator with slip ring, with stator directly connected to the grid and with rotor interfaced through a back to back partial scale power converter. The converter consists of two conventional voltage source converters that are called Rotor Side Converter (RSC) and Grid Side Converter (GSC) and a common DC-link [3]. Consequently the DFIG can be regarded as a traditional induction machine with a nonzero rotor voltage.

Using the Concordia and Park transformation allows to write a dynamic model in a d-q reference frame from the traditional a-b-c frame as follows [10]:
Electromagnetic torque:

$$T_{em} = \frac{3}{2}(\psi_{ds}i_{qs} - \psi_{qs}i_{ds}) \quad (6)$$

Active and reactive power of stator:

$$P_s = \frac{3}{2}(V_{ds}i_{ds} + V_{qs}i_{qs}) \quad (7)$$

$$Q_s = \frac{3}{2}(V_{ds}i_{qs} - V_{qs}i_{ds}) \quad (8)$$

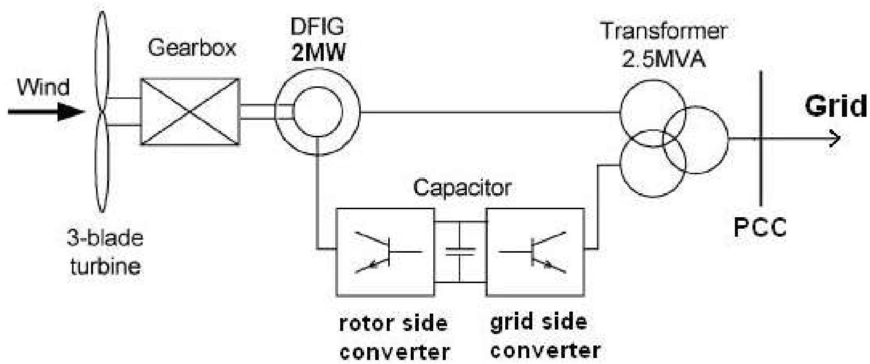


Fig. 3: Schematic representation of a DFIG wind turbine

Table 2: Induction generator parameters of wind turbine (DG2)

Rated power	2 MW
Rated voltage	0.69 kV
Stator/rotor ratio	0.4333
Angular moment of inertia(J=2H)	1.8293 p.u.
Mechanical damping	0.02 p.u.
Stator resistance	0.0183 p.u.
Rotor resistance	0.0205 p.u.
Stator leakage inductance	0.2621 p.u.
Rotor leakage inductance	0.3152 p.u.
Mutual inductance	5.572 p.u.

Table 2 shows the parameters of the induction generator which is used in this study. The rotor side converter operates at the slip frequency. The power converter processes only the slip power, thus if the DFIG to be varied within about ±30% slip, the rating of power converter is only about 30% of rated power of the wind turbine [11].

Setting the stator flux vector to align with *d*-axis and assuming the per phase stator resistance negligible, we have:

$$\psi_s = \psi_{ds}, V_s = V_{qs} \quad (9)$$

$$|\psi_s|\angle\theta_s = \int (V_s - r_s i_s) dt \quad (10)$$

Substitution (9) in (7) and (8), the active and reactive power of stator flow into the grid can be expressed as:

$$P_s = -\frac{3}{2}\frac{L_m}{L_m + L_s} V_s i_{qr} \quad (11)$$

$$Q_s = \frac{3}{2}\frac{V_s}{L_m + L_s}(L_m i_{dr} - \frac{V_s}{\omega_s}) \quad (12)$$

Where, i_{qr} and i_{dr} are rotor current (A) in d- and q-axis respectively, L_{ls} and L_m are stator leakage and mutual inductance (H), ω_s is the electrical angular velocity (rad/s) and V_s is the magnitude of the stator phase voltage (V). This means that using vector control with d-axis oriented stator flux vector in rotor side converter, active and reactive power can be controlled separately. This will be achieved by regulating i_{qr} and i_{dr} respectively.

Grid side converter is presented for keeping DC-link voltage of capacitor constant regardless to the magnitude and direction of rotor power. Neglecting power losses in the converter, capacitor current can be described as follow:

$$i_{dc} = C\frac{dV_{dc}}{dt} = \frac{3}{4} m i_{gcd} - i_{dcr} \quad (13)$$

Where i_{gcd} stands for the *d*-axis current flowing between grid and grid side converter (*A*), i_{dcr} is the rotor side DC current (*A*), C is the DC-link capacitance (*F*) and m is the PWM modulation index of the grid side converter.

The reactive power flow into the grid from GSC can be expressed as:

$$Q_g = \frac{3}{2} V_g i_{gcq} \quad (14)$$

where V_g is the magnitude of grid phase voltage (*V*) and i_{gcq} is *q*-axis current of grid side converter (*A*). Therefore it is seen from (13) and (14), by adjusting i_{gcd} and i_{gcq}, DC-link voltage and Q_g can be controlled respectively.

PITCH CONTROL

To produce a maximum energy, the blade angle must be tuned with wind straightforward using pitch angle control of wind turbine blades. It is worth noticing that we can use this characteristic in abnormal conditions such as grid faults to protect generator from over speeding. In two different cases, an increasing rotor speed may be occurred; a wind speed as input power and an abnormal case due to a fault existence. These must be distinguished first, before a control takes place. When the output terminal voltage falls under 0.9 p.u and the rotor speed is increased, it means a fault is happened.

To actuate the event and to decrease the rotor speed, the pitch angle must be manipulated. An emergency pitch angle should be added with rate of $\pm$10(*deg/s/1000rpm*) for over speed protection.

Apart form the mechanical control, there is another electrical protection to protect doubly fed induction generator from over current and over voltage in abnormal situations, an active diode bridge crowbar is proposed. Crowbar circuit consists of a diode bridge that rectifies the rotor phase currents and a single IGBT in series with resistance $R_{crowbar}$. The diode bridge crowbar is usually preferred to other configurations because it uses less switches and it is controlled more easily. To remove crowbar as fast as possible an active crowbar is needed which is obtained using an IGBT as crowbar switch. If rotor current or DC-link voltage exceeds their limits which are considered 1.5 p.u, crowbar switch is activated and short circuits the rotor and rotor side converter. After a constant time delay if parameters come back under the limit, crowbar is deactivated and returns to normal situation. It should be noted that during crowbar activation, due to fault ride-through capability of DFIG, stator is still connected to the grid and produces active power but without any control on output active and reactive power because of rotor side converter disconnection, more over grid side converter acts as a STATCOM to regulate voltage. In addition, due to increment of rotor resistance with crowbar resistor, nominal torque occurs in higher speed and improves the generator stability.

FUZZY CONTROL

The control system is based on fuzzy logic. This type of control, approaching the human reasoning that makes use of the tolerance, uncertainty, imprecision and fuzziness in the decision-making process, manages to offer a very satisfactory performance, without the need of a detailed mathematical model of the system, just by incorporating the experts' knowledge into fuzzy rules. In addition, it has inherent abilities to deal with imprecise or noisy data; thus, it is able to extend its control capability even to those operating conditions where linear control techniques fail (i.e., large parameter variations).

As illustrated in Fig. 4, this paper focuses on fuzzy logic control based on mamdani's system. This system has four main parts. First, using input membership functions, inputs are fuzzified, then based on rule bases and inference system, outputs are produced and finally the fuzzy outputs are defuzzified and applied to the main control system. Error of inputs from their references and error deviations in any time interval are chosen as inputs. In this paper, these parts as illustrated in Fig. 5 are simulated in MATLAB and using a user defined interface, mfiles and Fortran codes, fuzzy logic control units in MATLAB are linked with main system in PSCAD/EMTDC software, therefore in any simulation time interval, both softwares work simultaneously. Inputs are sent to MATLAB and output fuzzy controllers are produced there and sent to PSCAD/EMTDC software for the main system. The output of fuzzy controller is the value that should be added to the prior output to produce new reference output.

Figure 6 shows the block diagram of rotor side converter to which fuzzy controllers are applied. The main objectives of this part are active power control and voltage regulation of DFIG wind turbine using output reactive power control. As illustrated in Fig. 6 rotor side converter manages to follow reference active (Pref) power and voltage (Vref) separately using fuzzy controllers, hysteresis current controller converter and vector control algorithm. Based on (11), (12) and Fig. 6, inputs of fuzzy controller are error in active and reactive power or voltage and the rate of changes in errors in any time interval. After the production of reference d- and q-axis rotor currents, they converted to a-b-c reference frame using flux angle, rotor angle and finally slip angle calculation and Concordia and Park transformation matrix. Then they applied to a hysteresis current controller to be compared with actual currents and produce switching time intervals of converter.

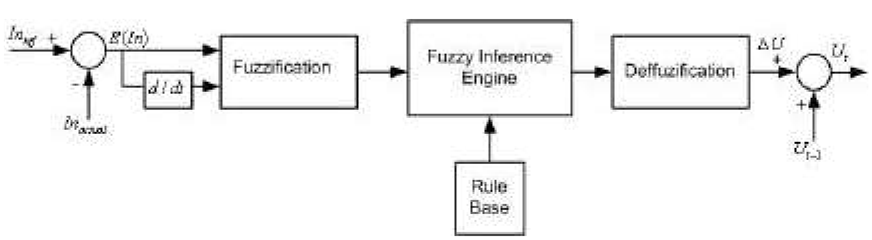


Fig. 4: Block diagram of fuzzy controller

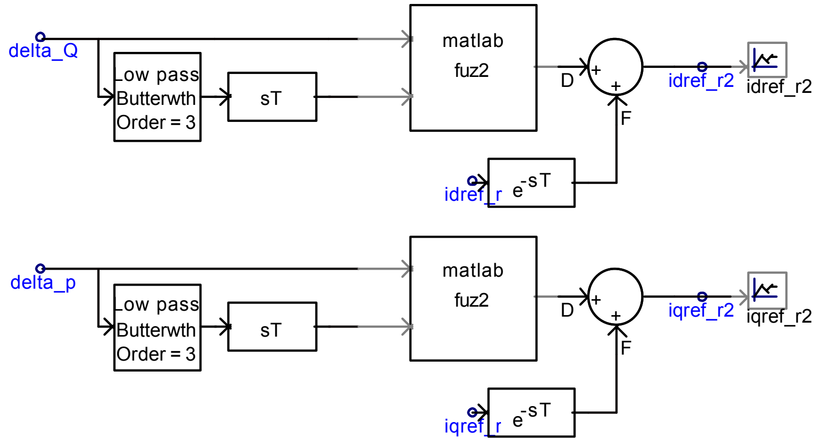


Fig. 5: Fuzzy controller interface with MATLAB in PSCAD/EMTDC environment

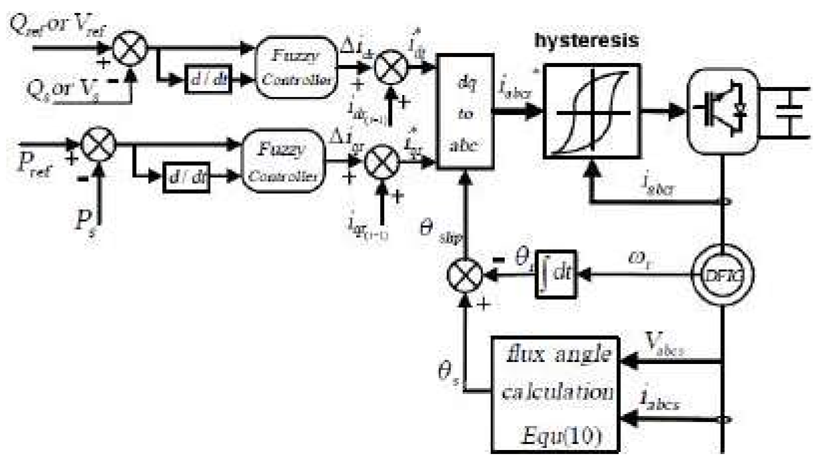
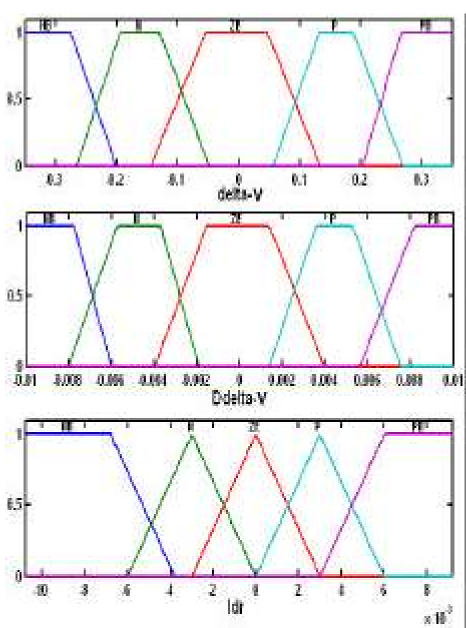


Fig. 6: Rotor side converter fuzzy controller unit structure



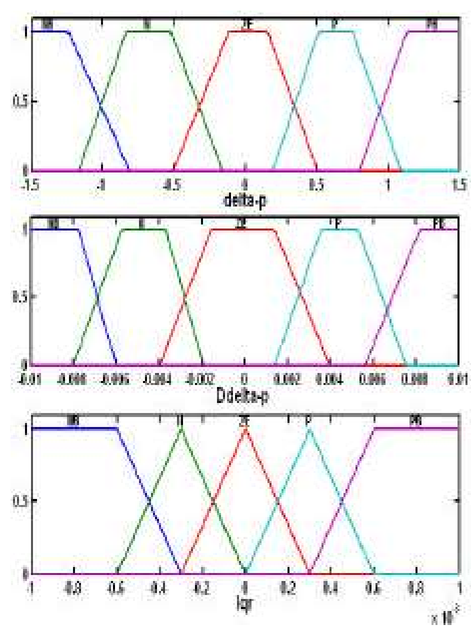


Fig. 7: Input and output membership functions of voltage controller

Fig. 8: Input and output membership functions of active power controller

Table 3: Rule bases of voltage fuzzy controller

		ΔE (V)				
ΔI_{dr}		NB	N	ZE	P	PB
E (V)	NB	NB	NB	N	N	ZE
	N	NB	N	N	ZE	P
	ZE	N	N	ZE	P	P
	P	N	ZE	P	P	PB
	PB	ZE	P	P	PB	PB

Table 4: Rule bases of active power fuzzy controller

		ΔE (P)				
ΔI_{qr}		NB	N	ZE	P	PB
E (P)	NB	NB	NB	N	N	ZE
	N	NB	N	N	ZE	P
	ZE	N	N	ZE	P	P
	P	N	ZE	P	P	PB
	PB	ZE	P	P	PB	PB

Figure 7 and 8 shows inputs and output membership functions. To avoid miscalculations due to fluctuations in wind speed and the effects of noise on data, trapezoidal membership functions are chosen to have smooth and constant region in the main points. Rule bases are shown in Table 3 and 4. NB, N, ZE, P and PB represents negative big, negative, zero, positive and positive big respectively. For instance when E (P), the error of active power and ΔE (P), the rate of change of active power error in a time interval, are NB mean the output voltage is more than reference and is increasing dramatically therefore reference q-axis rotor current which controls active power should decrease rapidly that represents NB.

RESULTS

For studying dynamic behavior of proposed system based on fuzzy logic controller, some different situations and events are considered. Based on different fault locations and severity, the system has different responses. In each condition, many different parameters such as wind speed, voltage, active and reactive power and etc are shown to prove the capability of the proposed controller.

Single line to ground fault near DG1: In this part a single line to ground short circuit fault with duration of 0.1s is applied near the synchronous generator (DG1). The fault is applied at 5s and is removed at 5.1s. Figure 9 shows, prior to fault active power and pitch angle of wind turbine varies based on wind speed to get

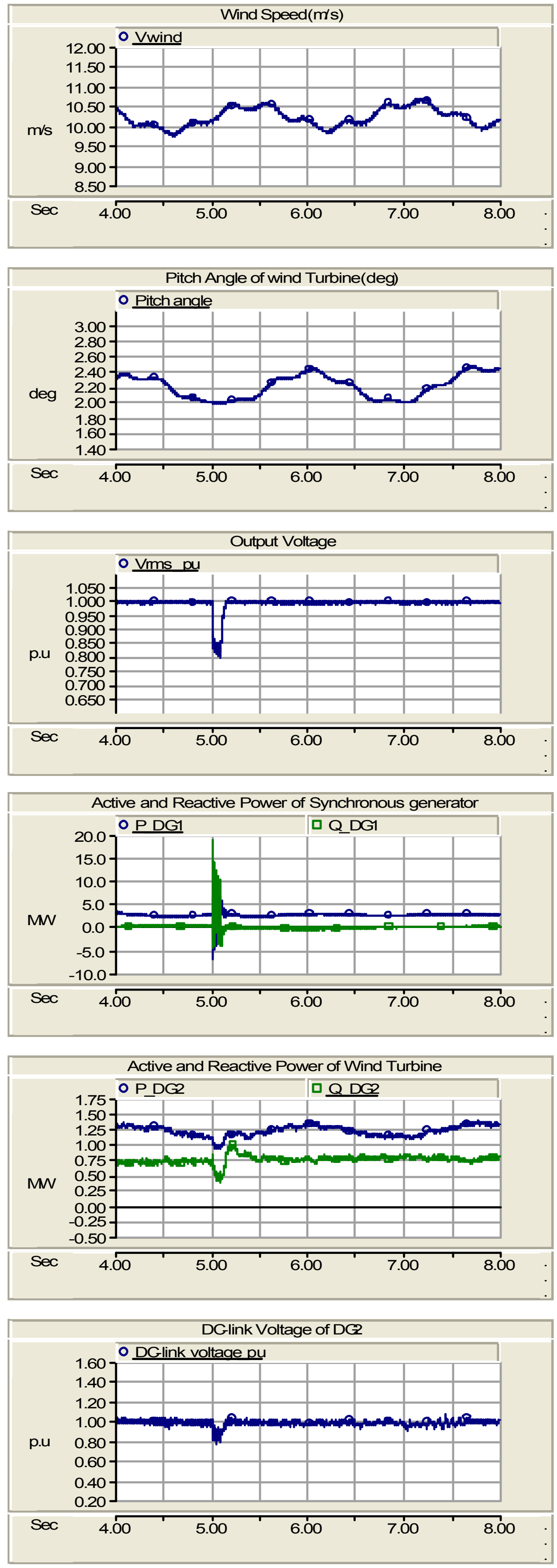


Fig. 9: Single line to ground fault near synchronous generator at 5s with duration of 0.1s

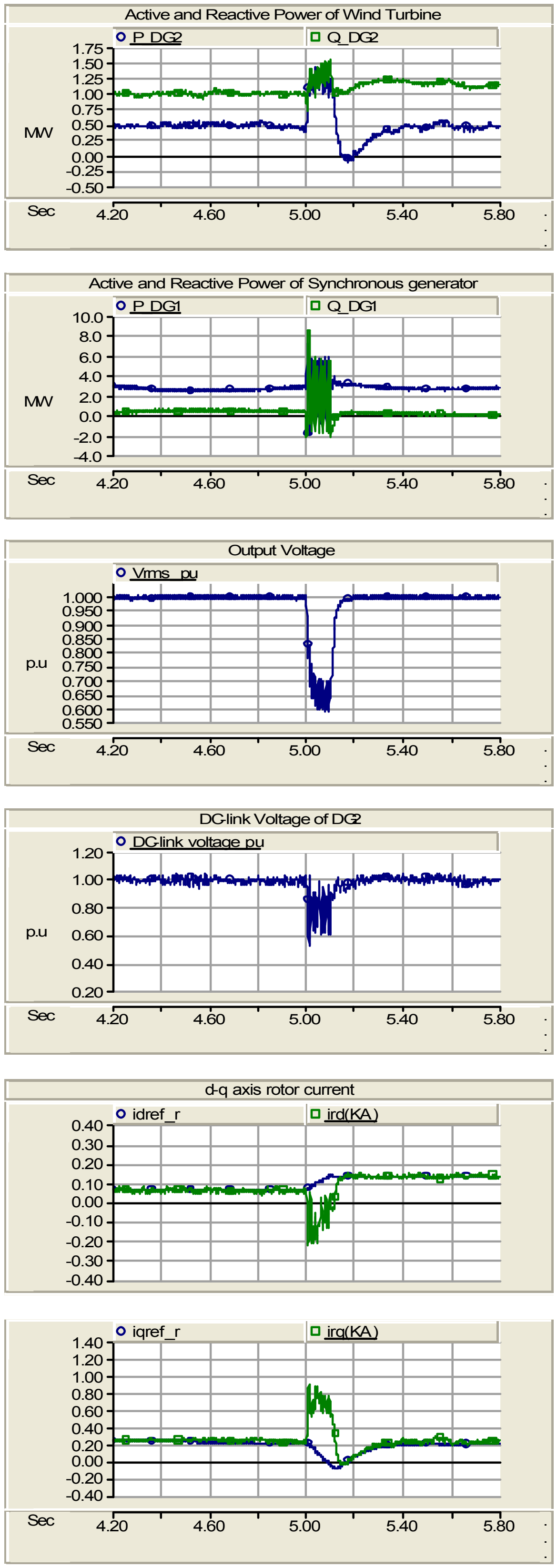


Fig. 10: Single line to ground fault near DFIG wind turbine

optimum wind power for the wind, which means it is working under variable speed operation that is one of the advantages of this kind of wind turbine in comparison with fixed speed wind turbines.

During the fault, we have a little change in active and reactive power of wind turbine and in other parameters such as AC and DC-link voltage because the fault is far from the wind turbine but deviations in active and reactive power of synchronous generator is high. Based on this situation, controller parts restore prior situations without any problem.

Single line to ground fault near DG2: Figure 10 illustrates, since the fault is near the wind turbine on bus 3, deviation in wind turbine parameters are more than the prior event. Voltage decreases until about 0.6 p.u and rotor current increases. In this part, an external active power reference is chosen therefore it is constant at 0.5 MW before the fault and comes back to predefined value after the fault clearance based on q-axis rotor current which follows its reference fantastically. Further more voltage using production of more reactive power returns to 1 p.u as soon as possible. This phenomenon occurs for other parameters and fuzzy control unit maintains stability and improves power quality of the power system.

Three line to ground fault near wind turbine: To prove performance of fuzzy logic controller unit operation and investigate dynamic behavior of doubly fed induction generator in one of the worst case situations, a severe three line to ground short circuit fault is applied near the wind turbine. Figure 11 shows, in this situation we have a dramatic reduction in voltage and it reduces to near zero. In addition, active and reactive deviations in DG2 are the most severe. Rotor current reaches to its limit and protection crowbar unit short circuits the rotor and rotor side converter but still stator is connected to the network and due to super synchronous operation of wind turbine it can produce active power. Further more, beside electrical protection, an emergency pitch angle is proposed to add which changes with slop of ±10 (deg/s). When voltage drops under 0.8 p.u and wind speed is constant, emergency pitch angle due to external fault is activated and increases to protect DFIG from over speeding and keep output power below rated value. As soon as voltage and speed come back to normal situation it starts to decrease and returns to normal situation.

In this period because of the short circuit of the rotor side converter we don't have any control on the output active and reactive power further more grid side converter acts as STATCOM and ties to restore voltage. After rotor current returns under the limit and a

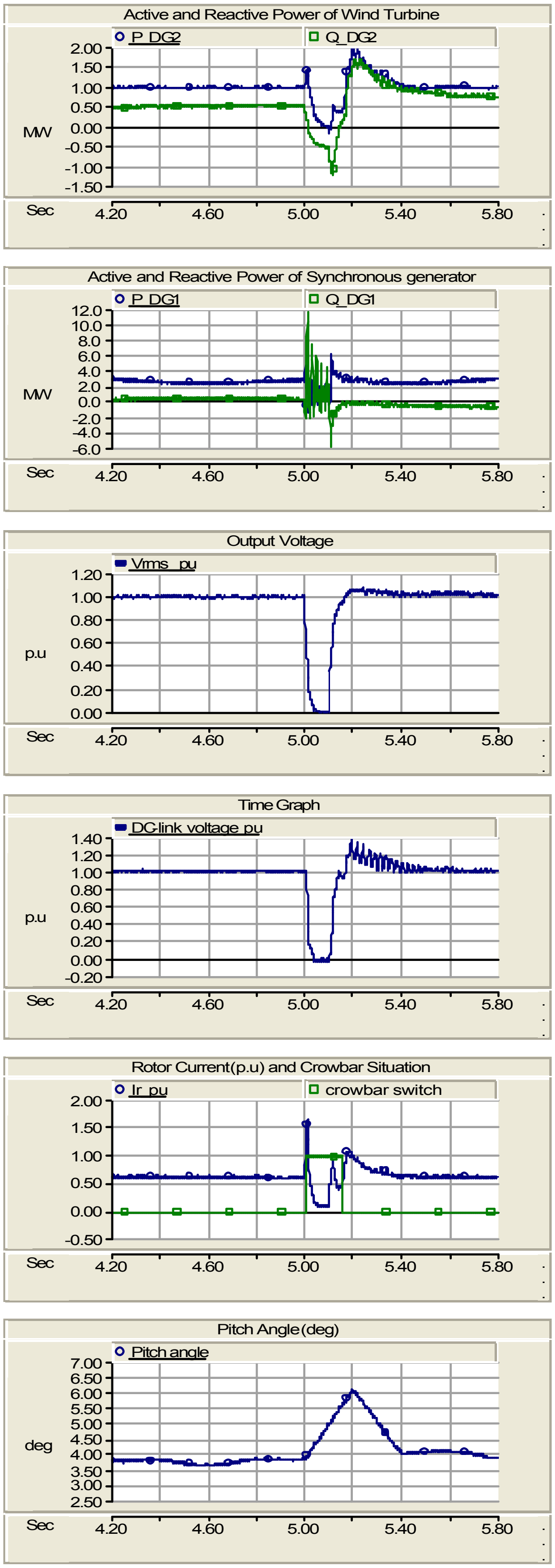


Fig. 11: Three line to ground short circuit fault near DFIG wind turbine

constant time delay, crowbar switch opens and rotor side converter continues to operate. As illustrated in Figure 11, although this condition is the worst, fuzzy control unit of wind turbine keeps stability and restores parameters to their predefined values as well.

CONCLUSION

This paper investigates fuzzy logic control of DFIG wind turbine. For this purpose a user defined block is used therefore both PSCAD/EMTDC and MATLAB softwares work simultaneously. All parameters and structures such as study system, wind turbine and control unit are described in details. To prove the performance of controller unit, different abnormal situations are exerted. Closer fault location to the wind turbine causes more severe situation and a three line to ground short circuit fault near the wind turbine as the worst case is studied in which voltage decreases until about zero and rotor current exceeds its limit. Crowbar switch as protection unit disconnects the rotor side converter and reconnect it after a constant time delay. After fault clearance, both electrical and mechanical control units using emergency pitch angle restore all parameters to their predefined values as soon as possible. Excellent performance of fuzzy logic controller using on-line tuning of parameters based on any situation maintains stability and improves power quality of wind turbine.

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