Fuzzy-based Direct Power Control of Doubly Fed Induction Generator-based Wind Energy Conversion Systems

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Abstract- **This paper proposes a new fuzzy-based direct power control (FDPC) for doubly fed induction generator (DFIG)-based wind energy conversion systems. In the proposed method, the required rotor voltages are directly calculated based on fuzzy controller, stator voltage, rotor speed and some machine parameters. The switching table and hysteresis comparator used in conventional DPC are replaced by PWM modulator. Also the converter switching frequency is constant. Furthermore, the effect of machine parameters mismatches is found negligible. Simulations are done to verify the effectiveness of proposed method under steady state and transient conditions and also machine parameters mismatches.**

Keywords-doubly fed induction generator (DFIG); direct power control (DPC); fuzzy logic controller(FLC)

I. INTRODUCTION

Wind energy has become an important source for electricity generation in many countries. It is expected that wind energy will provide about 10% of the world's electrical energy in 2020 [1].Nowadays, many wind farms are based on the doubly fed induction generator (DFIG) technology with converter rated at 20%-30% of generator rating. Compared with other wind farm technologies it offers several advantages such as increasedpower capture, decoupled and fast active and reactive powers control, reduced mechanical stresses[2-4]. A schematic diagram of the DFIG-based wind energy conversion systems is shown in Fig. 1.

Direct torque control (DTC) was first introduced in the middle of 1980s. DTCdirectly controls the developed torque by the machinewith the use of torque and flux information and selects the best voltage vector using switching look-up table [5]. Based on the DTC technique, the direct power control (DPC) was proposed for three phase pulsewidth modulated (PWM) converters and proven to have many advantages, such as simplicity, fast dynamics

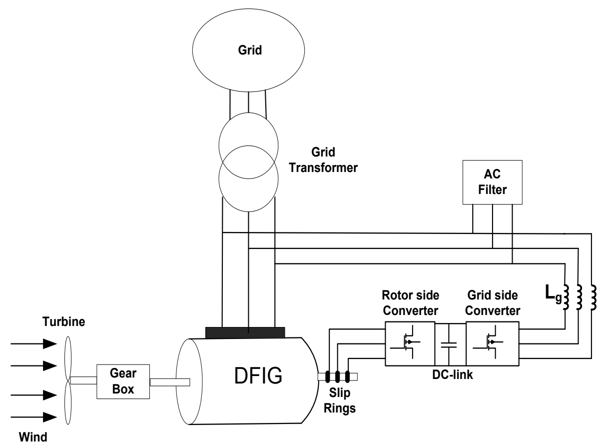

Figure 1.Schematic of a DFIG-based wind energy generation system.

and robustness against parameters variations and grid disturbances [6-8].In DPC, the converter switching states are selected from a switching table, based on the active and reactive powererrors and the angular position of the ac voltage [6, 7] or virtual flux [8]. Recently, the DPC is proposed for the control of acmotors [9] and more recently DFIG [10].In the proposed method reported in [10], the converter switching frequency changes due to the active and reactive power errors and hysteresis comparator bandwidth.

In this paper a new fuzzy-based direct power control (FDPC) strategy for DFIG is proposed. In the proposed method, direct power control is achieved based on the measured active and reactive powers, stator voltage, rotor speed and some machine parameters. Power errors and integration of power errors are fed as inputsto a fuzzy logic controller (FLC). The rotor reference voltages are directly calculated by adding output of FLC to the extra components namely therotor back emf. In the proposed method converter switching frequency is constant. The switching look-up table and hysteresis comparator are replaced by PWM modulator. It is also based on stator voltage orientation not stator flux orientation which removes need of integration.

II. DFIG MODELING AND EQUATIONS

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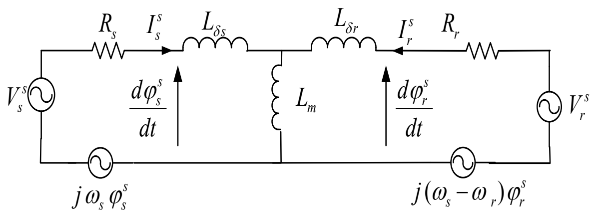

Figure 2.DFIG equivalent circuit in the synchronous reference frame.

The equivalent circuit of DFIG in the synchronous reference frame rotating at the speed of ω_s, is depicted in Fig. 2.

According to Fig.2, the stator and rotor voltages and flux vectors of DFIG can be expressed as

$$V_s^s = R_s I_s^s + \frac{d\varphi_s^s}{dt} + j\omega_s \varphi_s^s \tag{1}$$

$$V_r^s = R_r I_r^s + \frac{d\varphi_r^s}{dt} + j\left(\omega_s - \omega_r\right)\varphi_r^s \tag{2}$$

$$\varphi_s^s = L_s I_s^s + L_m I_r^s \tag{3}$$

$$\varphi_r^s = L_m I_s^s + L_r I_r^s \tag{4}$$

In the above equations, $L_s = L_{\delta s} + L_m$ and $L_r = L_{\delta r} + L_m$. The instantaneous active and reactive powers injected to the grid are given by

$$P_s + jQ_s = -\frac{3}{2} V_s^s \times I_s^s \tag{5}$$

The amplitude and rotating speed of the stator flux are constant under ideal grid voltages. Consequently, $d\left|\varphi_s^s\right| / dt = 0$.Assuming that the stator copper losses can be neglected, the stator voltage vector equation will be simplified as

$$V_s^s = j\omega_s \varphi_s^s \tag{6}$$

If, by using a PLL, the d-axis of the synchronous reference frame is fixed to the stator voltage vector, Eq. (6) results in

$$\varphi_{sd} = 0 \ , \varphi_{sq} = -V_{sd} / \omega_s \tag{7}$$

Based on Eqs.(3),(4), (5)and (7), active and reactive powers can be expressed as

$$P_s = K_\sigma V_{sd} \, \varphi_{rd} \tag{8}$$

$$Q_s = -K_\sigma V_{sd} \left(\frac{L_r}{L_m} . \frac{V_{sd}}{\omega_s} + \varphi_{rq}\right) \tag{9}$$

where $K_\sigma = \frac{3}{2} \frac{L_m}{\sigma L_s L_r}$.

Based on (8) and (9), since the stator voltage stays constant at normal operation, active and reactive power changes over a fixed sample periodT_s are given

$$\Delta P_s = K_\sigma V_{sd} \Delta\varphi_{rd} \tag{10}$$

$$\Delta Q_s = -K_\sigma V_{sd} \Delta\varphi_{rq} \tag{11}$$

According to (10) and (11), since changes in active and reactive powers are corresponding to the changes in rotor flux components in the d-q axis, the active and reactive powers can be controlled by adjusting $\Delta\varphi_{rd}$ and $\Delta\varphi_{rq}$ respectively. Equation (2) can be rearranged in each small sample periodT_s as follow

$$\frac{\Delta\varphi_r{}^s}{T_s} = V_r^s - R_r I_r^s - j\left(\omega_s - \omega_r\right)\varphi_r^s \tag{12}$$

After decomposing the (12) into d and q components and neglecting the rotor resistance effect, the changes in rotor fluxes are obtained as

$$\Delta\varphi_{rd} = T_s V_{rd} + T_s(\omega_s - \omega_r)\varphi_{rq} \tag{13}$$

$$\Delta\varphi_{rq} = T_s V_{rq} - T_s(\omega_s - \omega_r)\varphi_{rd} \tag{14}$$

Substituting (13) and (14) in (10) and (11), the rotor voltages in the synchronous reference frame are obtained as

$$V_{rd} = \frac{\Delta P_s}{T_s \, K_\delta \, V_{sd}\,(k)} + \frac{\omega_s - \omega_r}{K_\delta \, V_{sd}} Q_s + \frac{(\omega_s - \omega_r)\,L_r}{L_m \, \omega_s} V_{sd} \tag{15}$$

$$V_{rq} = -\frac{\Delta Q_s}{T_s \, K_\delta \, V_{sd}\,(k)} + \frac{\omega_s - \omega_r}{K_\delta \, V_{sd}} P_s \tag{16}$$

These equations are the base of proposed fuzzy-based direct power control (FDPC) method.

III. FUZZY-BASED DIRECT POWER CONTROL

With carefully considering (15) and (16), these equations can be rewritten as follow

$$V_{rd} = U_{rd} + E_{rd} \tag{17}$$

$$V_{rq} = U_{rq} + E_{rq} \tag{18}$$

where

$$U_{rd} = k_p \Delta P_s \tag{19}$$

$$U_{rq} = -k_q \Delta Q_s \quad (20)$$

$$E_{rd} = \omega_{slip} \left(\frac{Q(k)}{k_\delta V_{sd}(k)} + \frac{L_r V_{sd}(k)}{L_m \omega_s} \right) \quad (21)$$

$$E_{rq} = \omega_{slip} \frac{P(k)}{k_\delta V_{sd}(k)} \quad (22)$$

Based on (17)-(22), it can be concluded that rotor reference voltages are composed of two components. The first component is an output of proportional controller and k_p or k_q are the gain of these controller which are adopted to reduce the power errors. These controllers can be replaced by another proper controller. The second component is equivalent rotor back emf which is proportional to the slip angular frequency ($\omega_{slip} = \omega_s - \omega_r$).

In this paper, the fuzzy logic controller (FLC) is used instead of proportional controller mainly because of two reasons. First, it doesn't require any mathematicalmodel of the system or process which is under controlled. Second, it is widely accepted that the structure of FLC is simple and easy for practical implementation.

The power errors (e_p and e_q) and integration of power errors ($\int e_p$ and $\int e_q$) are used as inputs of FLC. The output of the FLC is proper voltage (U_{rd} and U_{rq}) to reduce the power errors which are added to equivalent rotor emf (E_{rdq}) to generate rotor reference voltages. Two independent FLCs are used to control active and reactive powers. For all inputs and outputs, seven fuzzy sets are chosen which are negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), positive big (PB). For example, the fuzzy set of active power error is depicted in Fig.4. The range of these variables in the horizontal axis is depended on the operating point of DFIG.

There are49 rules that form the knowledge repository of the FLC which are used to decidethe appropriate control action.These rules are presented in Table.1. The Sample rule of the FLC can be written as follow

*if (e_p (e_q) is x) AND ($\int e_p$ ($\int e_q$) is y) then (U_{rd} (U_{rq}) is w)*The performance of the fuzzy system is based on Mamdani's min–max rule [11, 12].

When a set of input variables is read, each rule is fired. For example, for the FLC of active power, the output of *i*th rule is as follow

$$\alpha_i = \min\left\{ \mu_p(e_p), \mu_{\int p}\left(\int e_p\right) \right\}$$

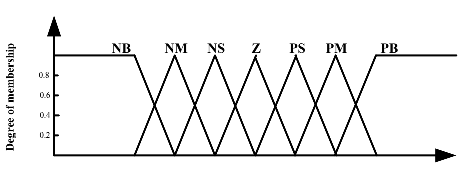

Figure 4.Fuzzy set of active power error.

TABLE.1 Rules of FLCs

e \ Δe	PB	PM	PS	Z	NS	NM	NB
PB	PB	PB	PB	PB	PM	PS	Z
PM	PB	PB	PB	PM	PS	Z	NS
PS	PB	PB	PM	PS	Z	NS	NM
Z	PB	PM	PM	Z	NM	NM	NB
NS	PM	PS	Z	NS	NM	NB	NB
NM	PS	Z	NS	NM	NB	NB	NB
NB	Z	NS	NM	NB	NB	NB	NB

whereμ_p and $\mu_{\int p}$ are membership functions of each input and α_i is the weighting factor (firing strength) of *i*th rule. Afterward, this value should be compared with the membership function of output in the *i*th rule. Thus

$$O_i = \min\{\alpha_i, \mu_{vi}\}$$

μ_{vi} and O_i are output membership function and final membership value of *i*th rule. To complete the Mamdani's min–max rule, the maximum value of final membership values of rules should be chosen. Based on this principle, the output that has maximum possibility distributionis chosen as the output. Thus the output is given as

$$\mu_v = \max\{O_i\} \quad i = 1, 2, ...$$

Finally the defuzzification method is used to produce the output voltage.Basically, defuzzification is a mapping from a space offuzzy control actions defined over an output universe ofdiscourse into a space of nonfuzzy (crisp) control actions.It is employed because in many practical applications acrisp control action is required.The shematicdiagram of the FDPC is depicted in Fig.5.

IV. SIMULATION

To investigate the performance of the proposed control strategy under different conditions, extensive simulations are conducted using Matlab/Simulink software. The simulated system is shown in Fig. 6 and the system parameters are given in Table 2. The DFIG is rated at 2 MW.

The grid side converter is responsible for balancing the power exchange between the rotor and grid through maintaining a fixed DC-link voltage.

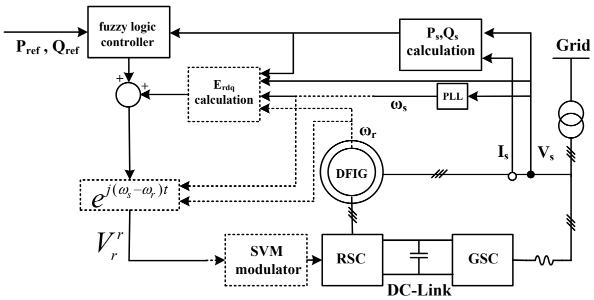

Figure 5.Schematic of proposed fuzzy-based direct power control.

The rotor side converter is intended to control the stator active and reactive powers. The control strategy of the grid side converter ispractically the same as VSC transmission systems [13] and grid-connected rectifiers [14]. In this paper, the proposed method in [14] is used and the DC-link voltage is adjusted at 1200 V.

A high frequency RC filter is connected to the stator side to absorb the switching harmonics and high frequency noises generated by the two converters. During the simulations, the sampling period was set to 250µs. To generate the switching pulses, the space vector modulation (SVM) technique with the switching frequency fixed at 2-kHz is utilized.

Various step changes in the active and reactive power references are carried out to evaluate the dynamic performance of the proposed DPC strategies. The results are shown in Fig. 7 for rotor speed of 1.2pu. Initially the rotor side converter is enabled with the active and reactive power references at 0 MW and -0.5 MVar, respectively. The active and reactive power references jumped from 0 to 2 MW at 0.2 s and from -0.5 to 0.5 MVar at 0.4 s, respectively. Then, step change of active power reference from 2 MW to 1 MW at 0.6 s is carried outto evaluate both rising and falling performances. The proposed control strategyreveals a fast dynamic response and the active and reactive powers track the reference values within a few milliseconds.

To verify that DFIG parameters variations don't make considerable effect on performance of control strategy, a simulation with 40% variation in mutual inductance and rotor speed variation was done. The results are depicted in Fig.8. As seen in Fig. 8, even with such large inductance errors and rotor speed variation the system response is good enough and the system maintains superior performance under both steady-state and transient conditions.

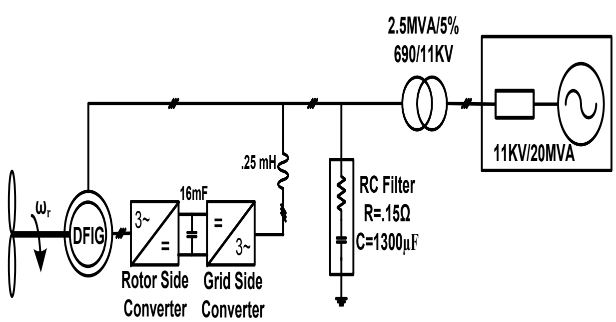

Figure 6.Configuration of the simulated system.

TABLE.2 Parameters of the simulated DFIG

Rated power	2MW
Stator voltage	690V
Stator/rotor turns ratio	0.3
R_s	0.0108pu
R_r	0.0121pu(referred to the stator)
	L_m3.362pu
$L_{\sigma s}$	0.102pu
$L_{\sigma r}$	0.11pu(referred to the stator)
Lumped inertia constant	0.2s
Number of pole pairs	2

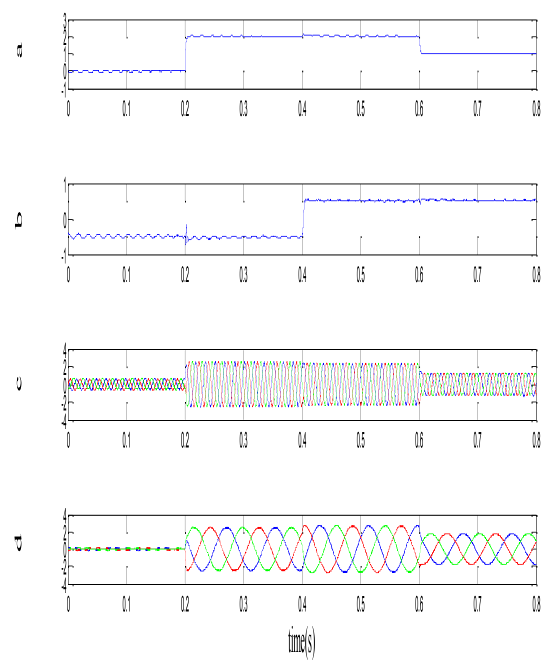

Figure 7. Transient performance of the proposed DPCs under various active and reactive power step changes at rotor speed of 1.2pu: a) active power (MW) b) reactive power (MVar) c) stator currents (kA) d) rotor currents (kA).

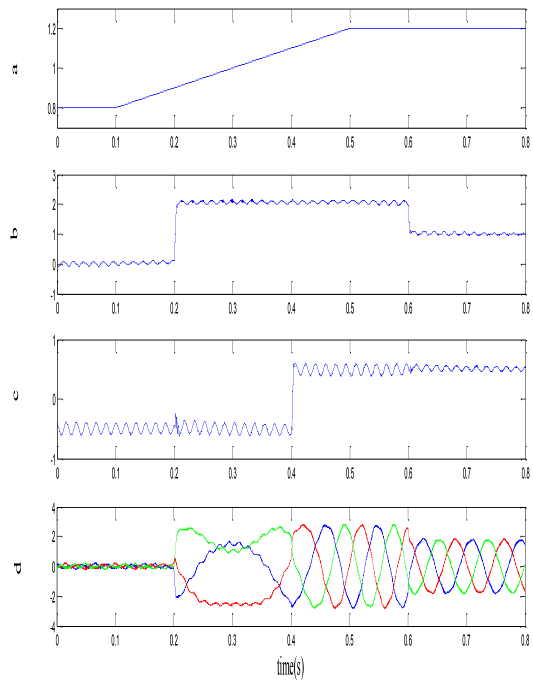

Fig.8. Simulated results under various stator active and reactive power steps and rotor speed variation and 40% variation in R_s and L_m. (a) Rotor speed(p.u) (b) Stator active power (MW) (c)Stator reactive power (MVar) (d) Three-phase rotor current (kA).

V. CONCLUSION

In this paper, a new direct power control method based on a fuzzy logic controller is proposed. At first, the mathematical model of DFIG in the synchronous reference frame is derived. Then, based on this model, the rotor reference voltages are directly calculated using fuzzy logic controller and feed forward term namely back emf. In the proposed method, the hysteresis comparator and switching look-up table are replaced by PWM modulator. Also, the converter switching frequency is constant. The extensive simulations were done which confirmthe effectiveness and superb performance of proposed method under steady state and transient conditionsand also machine parameters and rotor speed variations.

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