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Simulation of Wind-Driven DFIG Using Neuro-Fuzzy Vector Control Scheme

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Abstract: *Wound-rotor induction generators have numerous advantages in wind power generation over other types of generators. One scheme is realized when a converter cascade is used between the slip-ring terminals and the utility grid to control the rotor power. This configuration is called the doubly-fed induction generator (DFIG). A vector control scheme is developed to control the rotor side voltage source converter that allows independent control of the generated active and reactive power as well as the rotor speed to track the maximum wind power point. A neuro-fuzzy gain tuner is proposed to control the DFIG. The input for each neuro-fuzzy system is the error value of generator speed, active or reactive power. The choice of only one input to the system simplifies the design. Thus a control method to maximize power generation of a wind-driven DFIG considering the effect of saturation in both main and leakage flux paths is carryout using simulation.*

Keywords: *Doubly-fed induction generator (DFIG), neurofuzzy, vector control, wind power generation.*

1. Nomenclature

P_S, Q_S Real and reactive power.

V_S, I_S stator voltage and current.

V_{ds}, V_{qs} d- and q-axis components of the stator voltage.

V_{dr}, V_{qr} d- and q-axis components of the rotor voltage.

I_{ds}, I_{qs} d- and q-axis components of the stator current.

I_{dr}, I_{qr} d- and q-axis components of the rotor current.

I_{md}, I_{mq} d – and q –axis components of the magnetizing current.

λ_{ds} , λ qs d-and q-axis components of the stator flux linkage.

λ_{dr} , λ qr -d and q-axis components of the rotor flux linkage.

R_S, R_R Stator and rotor winding resistances.

X_{ls}, X_{LR} Stator and rotor leakage reactances.

X_m Magnetizing reactance.

X_S Stator reactance.

F_S Supply frequency.

Ws Rotor speed.

K_{P},K_{I} Proportional and integral gains.

P_m Mechanical power delivered by the turbine.

P r Active power delivered by the rotor to the converter.

Q_r Reactive power delivered by the rotor to the converter.

P_l Line-side active power.

Q l Line-side reactive power.

I_1 Line-side converter current.

I_2 Rotor-side converter current.

N Number of poles.

P Active power through the transmission line.

Q Reactive power through the transmission line.

C Capacitance.

2. INTRODUCTION

The use of doubly-fed induction generators (DFIGs) is receiving increasing attention for grid-connected wind power generation where the terminal voltage and frequency are determined by the grid itself. One configuration is realized by using back-to-back converters in the rotor circuit and employing vector control. This allows the wind turbine to operate over a wide range of wind speed and, thus, maximizes annual energy production. The 750-kW and 1.5-MW turbines and the 3.6-MW prototypes for offshore applications from GE Wind Energy Systems employ vector control of the DFIG rotor currents which provides fast dynamic adjustment of electromagnetic torque in the machine . Fuzzy logic has been successfully applied to control wind driven DFIGs in different aspects. In fuzzy logic was used to control both the active, and reactive power generation. A fuzzy logic gain tuner was used to control the generator speed to maximize the total power generation as well as to control the active and reactive power generation through the control of the rotor side currents as demonst in Appendix A. The error signal of the controlled variable was the single variable used as an input to the fuzzy system.

In the above-mentioned applications, the design of the fuzzy inference system was completely based on the knowledge and experience of the designer, and on methods for tuning the membership functions (MFs) so as to minimize the output error. To overcome problems in the design and tuning processes of previous fuzzy controllers, a neuro-fuzzy based vector control technique is first proposed by the authors to effectively tune the MFs of the fuzzy logic controller while allowing independent control of the DFIG speed, active, and reactive power. The proposed neuro-fuzzy vector controller utilizes six neuro-fuzzy gain tuners. Each of the parameters, generator speed, active, and reactive power, has two gain tuners. The input for each neuro-fuzzy gain tuner is chosen to be the error signal of the controlled parameter. The machine model is then used to build and simulate a neuro-fuzzy vector controlled wind- driven DFIG system.

The controllers used in vector control are a set of standard PI controllers with neuro-fuzzy gain schedulers. In these controllers, both proportional and integral gains are scheduled based upon the value of the error signal of the speed, active, or reactive power as discussed above. The neuro-fuzzy systems are designed and trained to provide the best dynamic performance while tracking the wind turbines maximum power point curve. Experimental investigations have also been conducted on a 2-kWlaboratory DFIG to verify the calculated results.

3. PROPORTIONAL AND INTEGRAL GAIN TUNERS

3.1 Conventional PI, Adaptive, and Fuzzy Gain Tuners

Conventional vector controllers and utilize a PI controller with fixed proportional and integral gains, and, determined by the zero/pole placement. Such controllers give a predetermined system response and cannot be changed easily. As the system becomes highly nonlinear, more advanced control schemes are required. In an adaptive controller is proposed by the authors that can schedule both and depending on the value of the error. Different characteristics such as linear, exponential, piece-wise linear and fourth-order functions, representing the variation in and as a function of the absolute value of the error are used. The coefficients were selected such that, for the proportional gain, a fast system response with less overshoot and small settling time is obtained.

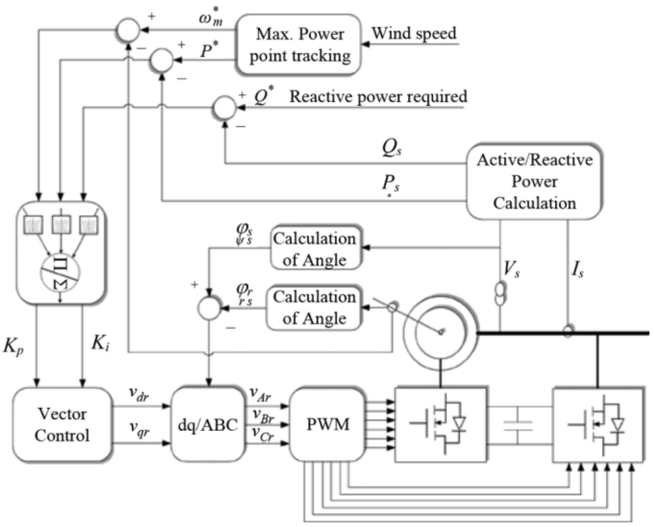


Fig. *Neuro-fuzzy gain scheduler for vector control of wind-driven DFIG*

While for the integral gain, it is required to reduce the overshoot and to eliminate the steady state error. It has been found that the performance of the system using the exponential characteristic produces the best system response with less overshoot, less settling time, and steady-state error. A fuzzy algorithm for tuning these two gains of the PI controller is proposed to produce good control performance Neuro-fuzzy gain scheduler for vector control driven DFIG. when parameter variations take place and/or when disturbances are present. This approach uses fuzzy rules to generate proportional and integral gains. The design of these rules is based on a qualitative knowledge, deduced from extensive simulation tests of a conventional PI controller of the system for different values of and, for operating conditions.

3.2 Proposed Neuro-Fuzzy Gain Tuner

In the neuro-fuzzy system, a learning method similar to that of neural network is used to train and adjust the parameters of the membership functions. Neuro-adaptive learning techniques provide a method for the fuzzy modeling procedure to learn information about a data set. The vector control technique is implemented .the wind speed is measured in order to determine the set values for both the maximum DFIG output power and the corresponding generator speed in order to track the maximum power curve. The absolute value of the error signal is used to calculate the scheduled proportional and integral gains using the neuro-fuzzy controller for each of the speed, active and reactive power controllers.

To apply the vector control to the DFIG system, six neuro-fuzzy gain tuners are trained offline. Two for each of active power, reactive power, and speed controllers. One unit is responsible for tuning the proportional gain and the other for tuning the integral gain. The developed neuro-fuzzy system is a first-order Sugeno type which has a single input with ten Gaussian distribution membership functions. It has ten *if–then* rules. The training data used are collected from extensive simulations of the vector controller system with various PI gains so that the trained tuner can tune the PI gains online based on the knowledge of the different PI controllers under different operating conditions.

Table 1. *Parameters of the Linear Output Membership Functions of the Speedcontroller*

	Proportional Gain		Integral Gain	
	p_i	r_i	p_i	r_i
MF 1	-387.0	-339.1	175.9	179.9
MF 2	-203.3	-117.4	52.38	46.06
MF 3	-171.7	-53.78	38.23	32.38
MF 4	-26.53	18.04	-1.405	19.37
MF 5	-197.6	3.579	26.85	23.29
MF 6	-63.12	26.77	-63.06	27.92
MF 7	-0.272	21.15	-7.523	19.54
MF 8	95.26	-14.91	-72.93	50.47
MF 9	146.9	-65.40	-79.23	70.89
MF 10	373.0	-323.0	-190.5	196.1

Table 2. *Parameters of the Linear Output Membership Functions of the Active And Reactive Power Controllers*

	Proportional Gain		Integral Gain	
	p_i	r_i	p_i	r_i
MF 1	-95.32	-56.11	140.6	142.8
MF 2	-15.95	13.24	16.96	26.35
MF 3	-4.948	22.90	5.534	17.16
MF 4	-2.390	11.85	6.732	29.42
MF 5	-2.023	11.63	3.208	28.50
MF 6	2.023	11.63	-3.208	28.50
MF 7	2.390	11.85	-6.732	29.42
MF 8	4.948	22.90	-5.534	17.16
MF 9	15.95	13.24	-16.96	26.35
MF 10	95.32	-56.11	-140.6	142.8

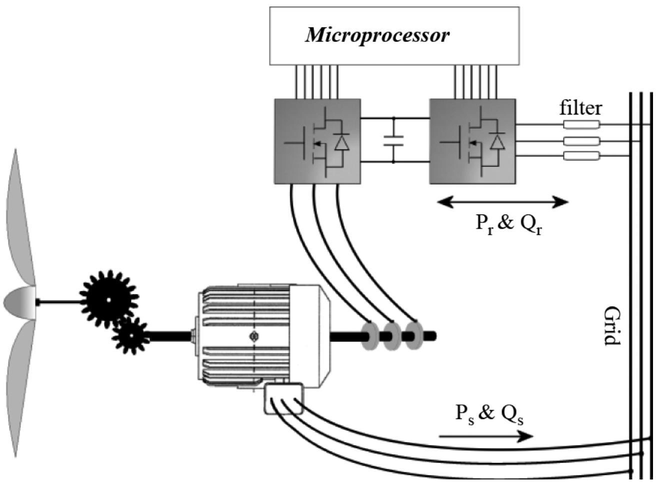


Fig. *Wind-driven DFIG system configuration.*

The proportional and integral gains are inputs to the standard PI controller part of the vector controller to generate the control signals and . Then and along with the stator and rotor angles are used to generate signals for the back-to-back converter. The angle and are calculated as in Appendix A. These angles along with and help evaluate a three-phase stator voltage signal that is sent to a to generate switching pulses for the back-to-back converters.

4. SIMULATION RESULTS FOR SUBSYNCHRONOUS AND SUPER-SYNCHRONOUS OPERATIONS OF THE DFIG

The system considered in this paper is a grid connected wind driven DFIG with the rotor circuit connected to the grid through back-to-back PWM voltage source converters in a configuration. While the rotor-side converter controls the rotor speed and the active and reactive power output through d- and q-axis components of the rotor voltage, and , by using fuzzy-based vector control strategy outlined previously, the grid side converter is controlled to maintain a constant voltage level across the coupling capacitor as demonstrated . A transformer is usually used in the rotor circuit due to the different levels between the stator and the rotor. Also, a filter is utilized to minimize the harmonics injected into the grid due to the switching of the power electronic devices.

4.1 DFIG Used in the Investigations

The 2-Kw DFIG used for the investigations is driven by a laboratory dc motor. The parameters of this machine are presented. The DFIG parameters have been determined by conducting dc, no-load, and locked-rotor tests on the machine. These tests are explained in the IEEE standard of Test Procedure for Poly-Phase Induction Motors and Generator and produce unsaturated machine parameters. In order to obtain a more realistic representation of the machine, saturation in the magnetic circuit along the main and leakage flux paths should be included in the machine model.

To determine the saturation characteristics of them a gnetizing, stator and rotor leakage inductances, two unconventional tests are carried out. The no-load generator test at synchronous speed is carried out to determine the main flux saturation characteristics. The terminal voltage–armature current curve with the machine unloaded and unexcited, and the open circuit characteristics are determined twice; one on the stator and the other on the rotor, to determine the stator and rotor leakage inductance saturation characteristics in respectively. This main flux path saturation has been represented in the generator model by modifying the unsaturated magnetizing inductance corresponding to the magnetizing current using .In order to take the leakage flux saturation into account ,the unsaturated stator and rotor leakage inductances in the machine model have been modified employing the stator and rotor leakage inductance saturation characteristics in respectively.

4.2 Maximum Power Point Tracking

The output power changes as a function of the wind speed as well as the generator speed as shown in Fig. 8. To track the maximum point, a lookup table is generated based on for wind speeds less than 12 m/s and saved into the neuro-fuzzy vector controller. Wind speeds higher than 12 m/s are beyond the scope of this research.When the measured wind speed changes, the lookup table will be searched to find the set values for both the maximum output power and the generator speed corresponding to the maximum power point. Although measuring the wind speed may have some drawbacks, it is the most accurate and easy way to change the generator speed in order to maximize the power generation.

4.3 Sub- and Super-Synchronous Operations of the DFIG

The performance of the system employing the proposed neuro fuzzy gain tuner is examined under different operating conditions .Two cases are considered in this paper. The first case investigates the subsynchronous operation where the wind speed changes from 7 to 8 m/s . According to for the maximum power generation of 0.96 kWat a wind Speed of 8m/s the generator set speed increases from1200to1400 rpm. The second case investigates the super-synchronous operation where the wind speed changes from9 to 11 m/s at s. The set speed increases from 1600 to 1900 rpm according to the maximum power point curve .where the corresponding power output is 1.86 kW at a wind speed of 11 m/s. For both cases, the proposed neuro-fuzzy gain scheduler is employed. The speed response, stator current, rotor line voltage, and rotor current for subsynchronous operation while, for the super-synchronous operation.

5. Experimental Determination of the DFIG Performance using the Proposed Controllers

The main objective is to validate the simulation results obtained in the previous section as well as investigate the performance of the DFIG when using different controllers. The types of controllers considered are: adaptive gain scheduler fuzzy logic and neuro-fuzzy. While the system stability analysis employing these controllers is not the focus of this paper, the controllers were developed with system stability in mind and it was observed that the system was stable during all experiments. As frequent and rapid changes of the controller gains may lead to instability, there is a limit as to often and how fast the controller gains can be changed. The conventional pI controller has a proportional gain of 45 and an integral gain of 22.5. The DFIG used in this experiment is coupled to a dc motor . The dc motor can be used as a prime-mover in wind turbine applications to adjust speed and deliver the required torque.

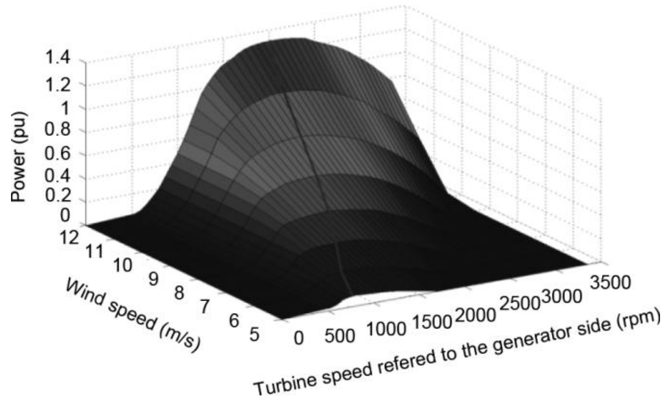


Fig. 8. *Typical wind turbine power curves for different wind speeds showing maximum power point curve.*

Numerous cases were considered and, for illustration purposes, two were chosen and will be demonstrated. For the ease of comparison, these two cases are chosen to be same as the two described in the simulation section. The first case investigates the subsynchronous operation of the DFIG with different controllers while the second case investigates the super-synchronous operation.

6. CONCLUSION

This paper presents a control method to maximize power generation of a wind-driven DFIG considering the effect of saturation in both main and leakage flux paths. This is achieved by applying vector control techniques with a neuro-fuzzy gain scheduler. The overall DFIG system performance using the proposed neuro-fuzzy gain tuner is compared to that using the conventional PI controllers. The generator speed response as well as the stator and rotor currents and the rotor voltages in response to a sudden change in the wind speed are presented. The main findings of the paper can be summarized in the following points:

1) Traditional vector control schemes that employ a conventional PI controller with fixed proportional and integral gains give a predetermined response and cannot be changed. However, the proposed neuro-fuzzy PI gain scheduler enables proportional and integral gains within the vector control scheme to be changed depending on the operating conditions.

2) It is demonstrated that, using the proposed controller, the system response can be improved and more precise control is achieved.

3) The proposed neuro-fuzzy PI gain scheduler achieves faster system response with almost no overshoot, shorter settling time, and no steady-state error.

Vector Control: The vector control technique allows decoupled or independent control of both active and reactive power. This section reviews the basic vector control strategy in the case of DFIG. The stator flux oriented rotor current control, with decoupled control of active and reactive power, is adapted in this paper. The control schemes for the DFIG are expected to track a prescribed maximum power curve for maximum power capturing and to be able to control the reactive power generation. The total active and reactive power generated can be obtained from the stator voltage and the - and -axis components of the stator current and can be expressed as

$$P_S=3/2|V_S|i_{qs} \quad \text{(A1)}$$

$$Q_S=3/2|V_S|i_{ds}$$

The field oriented control is based on the -axis modeling, where the reference frame rotates synchronously with respect to the stator flux linkage. The direct axis of the reference frame overlaps the axis of stator flux making the -axis component of stator flux . In such a case, the following expression is obtained:

$$\lambda_{qs}=X_S i_{qs}+X_m i_{qr}$$

$$=0 \qquad \text{(A2)}$$

Using (A2) and the active power equation in (A1), the equation of the active power can be rewritten as follows:

$$P_S=-(3X_m/2X_m)\ |V_S| i_{qr}. \qquad \text{(A3)}$$

The -axis component of stator current can be written as

$$I_{ds}=i_{md}-i_{dr}$$

$$=[|V_S|\ /(2\pi f_S X_m]-i_{dr} \qquad \text{(A4)}$$

Using (A4) and the reactive power in (A1), the equation of the reactive power can be rewritten as follows:

$$Q_S=3/2|V_S|[[|V_S|\ /(2\pi f_S X_m)]-i_{dr}]. \qquad \text{(A5)}$$

Therefore, it can be seen from (A3) and (A5) that the –axis component of the rotor current can be controlled to regulate the stator reactive power while the -axis component of the rotor current can be controlled to regulate the stator active power. As a result, the control of the stator active power via and the control of the stator reactive power via are essentially decoupled and, thus, a separate decoupler is not necessary to implement field orientation control for the slip power recovery. The calculation of the stator and rotor angles requires information pertaining to the stator current, rotor speed and machine parameters. The stator flux angle can be calculated from the following equation:

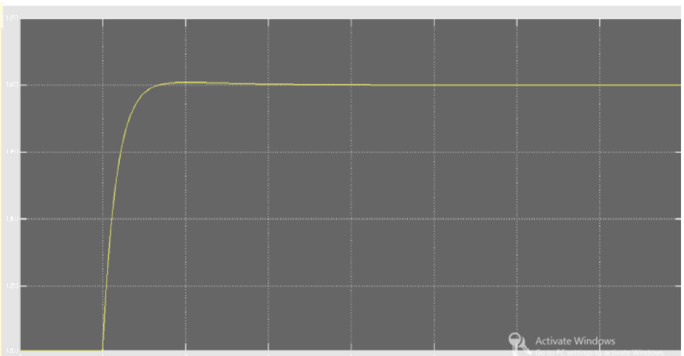
$$\varphi_S=\tan^{-1}[i_{Qs}\ /i_{Ds}\ ] \qquad \text{(A6)}$$

rotor angle can be calculated as

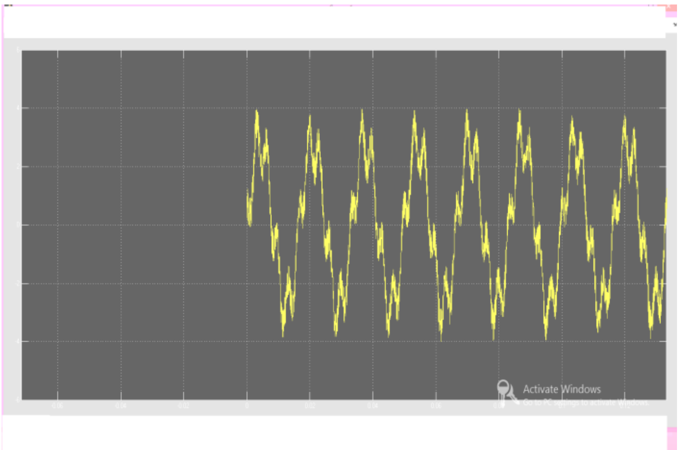
$$\Phi_r=\int(W_r+W_{Sl})dt$$

$$W_{Sl}=R_r/L_r\ L_m i_{qS}/\lambda_{dr} \qquad \text{(A7)}$$

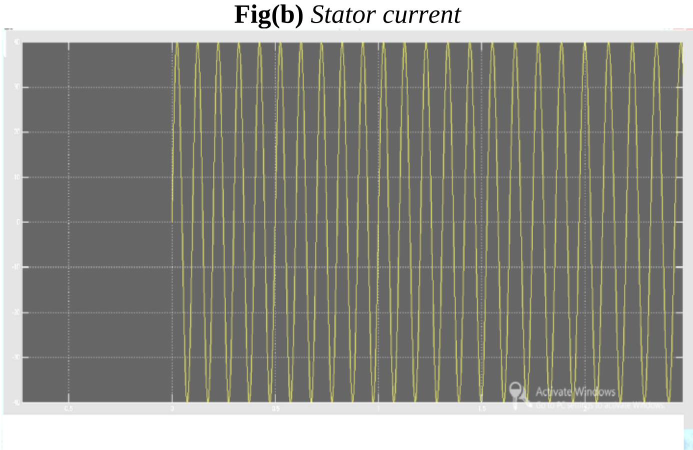
Simulation Results:



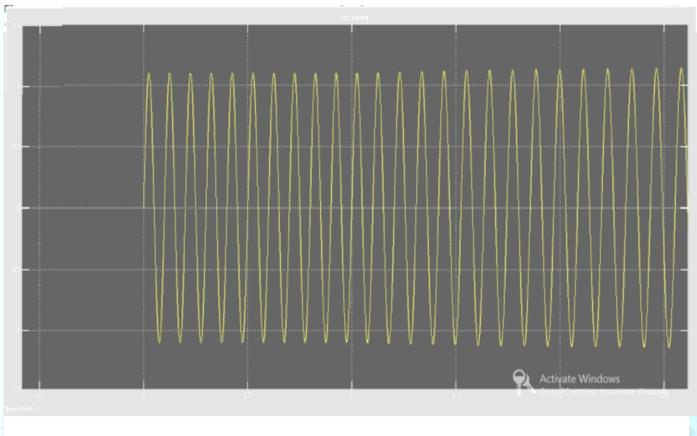
Fig(a) *Speed response*



Fig(b) *Stator current*



Fig(c) *Rotor line voltage*



Fig(d) *Rotor current*

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