Optimized Control of a Self Excited Induction Generator for Power Quality Improvement

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Abstract— In the present era, Non-conventional energy generation systems, contributing a high percentage in power generation. Among the non-conventional energy generation systems, wind energy generation is the most important one for the power grid. The doubly-fed induction generator (DFIG) is currently the system of choice for multi-MW wind turbines. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, presently DFIG based wind turbines are quite popular as it can extract maximum power. Though the DFIG based wind turbines can provide maximum extent of power but generally suffer from the power oscillation during wind speed variations, to overcome this problem this work proposes a novel PID type Fuzzy Controller (PIDFC) for efficient pitch angle control of DFIG system for wind power generation, so that the DFIG based wind turbines not only able to provide maximum power but the power obtained will be highly stable also, irrespective to the wind speed fluctuations. For the comparative analysis, a comparison is also presented between the conventional PI controller and proposed PIDFC controller. The obtained result indicates that, the proposed method is highly efficient to sustain the power oscillations as compare to state of art techniques. In addition to this it is also found that, the proposed PIDFC based pitch angle controller takes 80% less settling time as compare to conventional PI controller.

Key words: Non-conventional energy, wind power generator, DFIG, pitch angle control, PI controller, PID type Fuzzy controller

I. INTRODUCTION

The increasing wind generation with long-distance power transmission in electrical power grids raises reasonable concern of possible stability threats to the system security operation and control. In such situations, how to design an adaptive, optimal controller becomes a critical challenge faced by the power grid operators and engineers around the world today.

Doubly-fed induction generators (DFIGs) are the most widely used wind power generators in wind power generation systems [1]. It has been recognized that the controllers have a critical impact on the stability performance of grid connected DFIG. Therefore, the controllers should be designed appropriately [2]. Among all the control designs, reactive power control is an important issue for the grid-connected wind farms [3]–[5]. Many wind power grid connection codes today require the enhancement of the low voltage ride through (LVRT) capability of wind farms and the maintenance of their reliability in a certain range during and after a short-term fault. The study in [3] shows that rotor angles of synchronous generators are directly influenced by the type of reactive power control employed by the wind generation. The implementation of appropriate control strategies in wind farms, particularly the terminal voltage control, can lessen the reactive power requirements of conventional synchronous units and help to mitigate large rotor angle swings. Meanwhile, it is suggested that a good control strategy for the static synchronous compensator (STATCOM) will significantly improve the system dynamics [6], [7]. Based on this suggestion, an approach to conduct an impact study of a STATCOM on the integration of a large wind farm into a weak loop power system is presented in [8]. Here it is illustrated that the size and location of the STATCOM will both affect the voltage fluctuations.

A decoupled control technique for the active and reactive power of doubly-fed wound rotor induction generator is proposed in [9], and it has been widely used in the control design of wind turbines (WT) with DFIG [10]–[12]. The control technique is based on the conventional proportional-integral (PI) control, which needs an accurate wind farm and power system model. Therefore, this technique requires a large number of parameters to be optimized or tuned to ensure a good interaction between the wind farm and the power system at the point of common coupling (PCC). For most of the research, the parameters of the PI controllers are tuned with approximate linearization using different optimization methods.

This paper proposes a novel PID type Fuzzy Controller (PIDFC) for efficient pitch angle control of DFIG system for wind power generation, so that the DFIG based wind turbines not only able to provide maximum power but the power obtained will be highly stable also, irrespective to the wind speed fluctuations. For the comparative analysis, a comparison is also presented between the conventional PI controller and proposed PIDFC controller.

II. DOUBLY-FED INDUCTION GENERATOR (DFIG) SYSTEM

Today, doubly-fed induction generators (DFIG) are more frequently used for the large wind power generation. Since their power electronic equipment only has to handle a fraction (20–30%) of the total system power. This means that the losses in the power electronic equipment can be reduced in comparison to power electronic equipment that has to handle the full system power as for a direct driven induction generator, apart from overall cost effectiveness. The semiconductor AC/DC and then DC/AC conversion is used to control the bidirectional power delivered from/to the rotor circuit to/from the grid.

A. Basic Operating Principle of DFIG

The doubly-fed induction generator (DFIG) is a ‘special’ variable speed induction machine and is widely used as modern large wind turbine generators. It is a standard, wound rotor induction machine with its stator windings directly connected to the grid and its rotor windings
connected to the grid through an AC/DC/AC pulse width modulated (PWM) converter. The AC/DC/AC converter normally consists of a rotor-side converter and a grid-side converter. By means of the bi-directional converter in the rotor circuit, the DFIG is able to work as a generator in both sub-synchronous (positive slip \( s > 0 \)) and over-synchronous (negative slip \( s < 0 \)) operating area. Depending on the operating condition of the drive, the power is fed in or out of the rotor. If \( (P_{\text{rot}} < 0) \): it is flowing from the grid via the converter to the rotor in sub-synchronous mode or vice versa \( (P_{\text{rot}} > 0) \) in over-synchronous mode. In both cases (sub-synchronous and over-synchronous) the stator is feeding energy to the grid \( (P_{\text{st}} > 0) \) [27].

For variable speed systems with limited variable-speed range, e.g. \( \pm 30\% \) of synchronous speed, the DFIG is reported to be an interesting solution. A detailed representation of DFIG with its back to back converters is depicted in Figure 2.1. The back-to-back converter consists of two converters, i.e., rotor-side converter (RSC) and grid-side converter (GSC), connected “back-to-back.” Between the two converters a DC-link capacitor is placed. With the rotor-side converter it is possible to control the torque or the speed of the DFIG. Doubly fed induction machines can be operated as a generator as well as a motor in both sub-synchronous and super synchronous speeds using the rotor side converter control. Only the two generating modes at sub-synchronous and super synchronous speeds are of interest for wind power generation.

\[ P_{\text{air}} = \frac{1}{2} \rho A_r \omega^2 \]

where \( \rho \) is the air density, \( \omega \) is the wind speed and \( A_r \) is the area swept by the wind turbine blades. However, the energy which can be extracted by the wind turbine is less than the energy in the wind. Therefore the power extracted by the aerodynamic rotor \( (P_m) \) is expressed with respect to the power available in the wind \( (P_{\text{air}}) \) as follows:

\[ P_m = C_p - P_{\text{air}} \]

(2.1)

C. \( P_m \) is called the power coefficient and depends on the tip-speed ratio (\( \lambda \)) which is the ratio between the velocity of the rotor tip and wind speed defined by:

\[ \lambda = \frac{\Omega_r r}{\omega} \]

(2.2)

where \( \Omega_r \) is the aerodynamic rotor speed and \( r \) is the radius of the rotor. To extract the maximum power from the wind, the rotor speed should vary with the wind speed, maintaining the optimum tip speed ratio \( (\lambda_{\text{opt}}) \). In practical DFIG wind turbine the rotor torque is used as a set point reference. A typical set-point torque-speed characteristics applied for controlling DFIG wind turbines is shown in Figure 2.3. The cut-in and the rated speed limits are mainly due to converter ratings although the upper rotational speed may also be limited by an aerodynamic noise constraint. For low-medium wind speeds (A-B) the speed control defined by the set point torque is applied by controlling the injected rotor voltage. When the rotor reaches pint B, blade pitch regulation dominates the control and limits the aerodynamic power. For very high wind speeds the pitch-control will operate until the wind speed shutdown limit is reached.

\[ 2\Delta \omega_r^{\max} \]

\[ \omega_m \]

\[ \Omega_r \]

\[ \lambda \]

\[ \lambda_{\text{opt}} \]

\[ \Omega_r \]

Fig. (2.1): Schematic of conventional DFIG wind system

Fig. (2.2): Speed-torque characteristics of DFIG system

B. Speed Control for Optimum Power

Wind turbines operate by exciting energy from the wind. The available energy in a wind stream is given by

\[ P_{\text{air}} = \frac{1}{2} \rho A_r \omega^2 \]

The speed–torque characteristics of the DFIG system can be seen in Figure 2.2. As also seen in the figure, the DFIG can operate both in motor and generator operation with a rotor-speed range of \( \pm \Delta \omega_r^{\max} \) around the synchronous speed, \( \omega_s \).
be regulated separately for speed control and/or voltage control, respectively. The DFIG wind turbine voltage control strategy is typically defined to provide power factor control of the induction generator, using converter C1. Terminal voltage control can also be provided through the rotor side converter and this scheme is illustrated in Figure 2.4. However, reactive power injection can be obtained from either the rotor side converter (C1) or the network side converter (C2). Using the rotor side converter (C1) is likely to be preferred to the network side converter for DFIG voltage control schemes. This is largely due to the reduction in the converter-rating requirement as reactive power injection through the rotor circuit is effectively amplified by a factor of 1/slip [28].

Fig. (2.4): Simplified schematic of a DFIG wind turbine typical control system

III. METHODOLOGY OF PROPOSED WORK

Doubly-fed induction generators (DFIGs) are the most widely used wind power generators in wind power generation systems. It has been recognized that the controllers have a critical impact on the stability performance of grid connected DFIG. Therefore the performance of the controller's plays very crucial role while generation of stabilized power.

During the study of conventional DFIG system it is observed that, the conventional DFIG based wind turbine system comprises PI controllers for maintaining the pitch angle in accordance with the change in wind speed. Since the PI controller is actually a low level controller, it doesn’t have a good efficiency to control pitch angle and its compensation during change in wind speed. Therefore this inability of PI controller rise to oscillations in generated power. To overcome this problem this work proposes a novel PID type Fuzzy Controller (PIDFC) for efficient pitch angle control and its compensation in DFIG system for wind power generation, so that the DFIG based wind turbines not only able to provide maximum power but the power obtained will be highly stable also, irrespective to the wind speed fluctuations.

This section first briefly describe the conventional DFIG based wind turbine test system used for this work and then present the development of proposed PIDFC controller based DFIG wind turbine system. For the implementation of the proposed work MATLAB Simulink 2012 (b) platform has been used.

A. Description of the Test System

A 9 MW wind farm consisting of six 1.5 MW wind turbines connected to a 25 kV distribution system exports power to a 120 kV grid through a 30 km, 25 kV feeder is developed. The proposed system having Wind turbines using a doubly-fed induction generator (DFIG) consist of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter.

The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. As the main objective of this work is to evaluate the performance of DFIG in variable air speed environment, and to achieve this significant fluctuations in the air speed has been created in the simulation. The variable air speed situation generated is shown in figure (3.1).

Fig. (3.1): the variable air speed situation generated.
The initial wind speed is maintained constant at 15 m/s and then it suddenly goes down to 10 m/s, and after this point the air speed increases gradually to 16 m/s up to time 2.5 sec.

The control system uses a torque controller in order to maintain the speed at 1.2 pu. The reactive power produced by the wind turbine is regulated at 0 Mvar. The sample time used to discretize the model is 50 microseconds. For a wind speed of 15 m/s, the turbine output power is 9 MW approximately, the pitch angle is 8.7 deg and the generator speed is 1.2 pu. Figure (3.2) shows the simulation model developed for the proposed work in MATLAB Simulink 2012b version.

![Simulation Model Developed for proposed test system.](image)

Figure 3.3 shows the pitch angle control structure of a conventional DFIG wind turbine system, in which two PI controller were used for pitch angle control and its compensation.

![Pitch angle control structure of a conventional DFIG wind turbine system.](image)

Because of the drawbacks mentioned above, a PID type fuzzy controller consisting of only the error and the rate of change of error is used in the proposed method. This allows PD and PI type fuzzy controllers to work in parallel. An equivalent structure is shown in Fig. 3.4, where \( \beta \) and \( \alpha \) are the weights of PI and PD type controllers, respectively. Similarly, \( K \) and \( K_d \) are the scaling factors for \( e \) and \( e' \), respectively. As the \( \alpha/\beta \) ratio becomes larger, the effect of the derivative control increases with respect to the integral control.

B. Development of Proposed Fuzzy PID (PIDFC) Based Pitch Angle Controller

1) PID Type Fuzzy Control

In order to design a PID type fuzzy controller (PIDFC), one can design a fuzzy controller with three inputs, error, and the change rate of error and the integration of the error. Handling the three variables is however, in practice, quite difficult. Besides, adding another input to the controller will increase the number of rules exponentially. This requires more computational effort, leading to larger execution time.
The output of the controller can be expressed as,

$$u_c = \alpha u + \beta \int u dt$$

This controller is called as PID type fuzzy controller (PIDFC).

2) **Development of Fuzzy PID Controller**

During the development of fuzzy controller two variables, error \( (e) \) which is the difference between reference and actual wind speed has been used as first input variable for designing of fuzzy controller. On the same time the rate of change of error signal \( (\dot{e}) \) has been taken as the second input variable for the fuzzy controller which is nothing but the first derivative of error \( (e) \). The fuzzy controller of proposed PID type Fuzzy Controller generates control signal named as \( u \). The membership functions of error \( (e) \), change rate of error \( (\dot{e}) \) and control signal \( (u) \), are shown from figure (3.5) to figure (3.7), are chosen as triangular membership functions.

The linguistic terms chosen for this controller are seven. They are negative large (NL), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM) and positive large (PL). After assigning the input, output ranges to define fuzzy sets, mapping each of the possible seven input fuzzy values of error \( (e) \), rate of change of error \( (\dot{e}) \) to the seven output fuzzy values is done through a rule base. Total 49 rules have been designed, to prepare rule base for proposed PIDFC controller few of them are given as

1) If \( (e \) is NB) and \( (\dot{e}) \) is NB) then \( (u \) is NB) (1)
2) If \( (e \) is NB) and \( (\dot{e}) \) is NM) then \( (u \) is NB) (1)
3) If \( (e \) is NB) and \( (\dot{e}) \) is NS) then \( (u \) is NB) (1)
4) If \( (e \) is NB) and \( (\dot{e}) \) is Z) then \( (u \) is NB) (1)
5) If \( (e \) is NB) and \( (\dot{e}) \) is PS) then \( (u \) is NM) (1)

After successful development of the proposed PID type fuzzy controller the modified control structure of the DFIG based wind turbine system simulation model is shown in figure (3.8).
Finally the internal structure of the developed PID type fuzzy controller (PIDFC) is shown in figure (3.9).

![Diagram of PIDFC Controller](image)

**Fig. (3.9): Structure of developed PIDFC Controller**

### IV. SIMULATION RESULTS FOR CONVENTIONAL DFIG WITH PI CONTROLLER AND PROPOSED PID TYPE FUZZY CONTROLLER (PIDFC) BASED DFIG

Let’s consider the variation in the wind speed shown in figure (3.1) and observe the turbine response to a change in wind speed with PIDFC controller and conventional PI controller.

Initially, wind speed is set at 15 m/s, then at \( t = 0.5 \) seconds, it suddenly goes down to 10 m/s, and after this point the air speed increases gradually to 16 m/s up to time 2.5 sec. The generated active power obtained for PIDFC controller based DFIG and PI controller based DFIG is shown in figure (4.1). The obtained result for active power generation from PIDFC based DFIG wind turbine system, shown in figure (4.2), it is clearly found that, the proposed PIDFC based DFIG system provides stable power generation not only in steady state part, but during the high wind speed variations.

![Plot of output power from PIDFC and PI controllers DFIG Wind Turbine](image)

**Fig. (4.1): Plot of output power from PIDFC and PI controllers DFIG Wind Turbine.**

![Plot of Reactive power from PIDFC and PI controllers DFIG Wind Turbine](image)

**Fig. (4.2): Plot of Reactive power from PIDFC and PI controllers DFIG Wind Turbine.**

![Plot of Controlled Pitch Angle from ANFIS and PI controllers DFIG Wind Turbine](image)

**Fig. (4.3): Plot of Controlled Pitch Angle from ANFIS and PI controllers DFIG Wind Turbine.**

From the above figure we can clearly observed the efficient pitch angle control ability of proposed PID type fuzzy controller (PIDFC) over PI controller. Initially when wind speed is kept constant on 15 m/s, the generated active power starts increasing to reach its rated value of 9 MW but settled down to 10 MW for PI controller based DFIG, while settled to constant 9 MW for proposed PIDFC controller. At \( t = 0.5 \) seconds, as the wind speed suddenly downed to 10 m/s, even then also the power was stabilized around 10 MW for PI controller and 9 MW for proposed PIDFC, but as the wind speed gradually increases from 10 m/s to 16 m/s, around \( t = 0.7 \) sec there is high oscillation in power occurs for PI controller based DFIG system, and this oscillation remains till \( t = 2 \) sec, while for proposed PIDFC controller based DFIG system the generated power remains stable at the rated 9 MW for this wind speed variation. After \( t = 2 \) sec the power generated by the PI controller based DFIG system again tends to stabilize at 10 MW. Although during the period of power oscillation PI controller tries to limit mechanical power by rapidly changing the pitch angle, but the effort was not found enough to overcome this oscillation, on the other hand the proposed controller PIDFC provides stable power generation on rated power of 9 MW.

### V. CONCLUSION

The increasing wind generation with long-distance power transmission in electrical power grids raises reasonable concern of possible stability threats to the system security.
operation and control. In such situations, how to design an adaptive, optimal controller becomes a critical challenge faced by the power grid operators and engineers around the world today.

In this paper, complete description of the DFIG system equipped with the PI controller and proposed PIDFC based controller for pitch angle control and compensation has been successfully described and implemented. In the result section it has been shown that, the developed PIDFC controller based DFIG system can able to provide efficient damping in the power oscillation during change in wind speed and hence provides constant power output at the transient state and keeps it constant during the steady state. While comparative plots of results shows that the conventional PI controller can provide controlled constant power after constant wind speed, and cannot able to maintain constant power during variable wind speed.

In addition to this it is also evident from the resultant plots, that conventional PI controller takes higher timing slot to maintain the constant power, while proposed PIDFC based controller takes 80 percent less time to sustain the power oscillation. Therefore this work has put forwarded a novel power oscillation damping strategy using PID type fuzzy controller (PIDFC) based pitch angle control and compensation during variable speed of wind.

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