Optimal Pitch Angle Control for Wind Turbine Using Intelligent Controller

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Abstract. Wind energy is the most plenty resource in the renewable energy purse. Increasing the wind pick out capability improves the economic viability of this technology, and makes it more rivalry with traditional fossil-fuel based supplies. Therefore, it is necessary to search control strategies that increase aerodynamic efficiency. Several controls are applied and compared during this research. The angle of blade pitch is employed to control the wind turbine (SCIG) operation during partial and full load operations, correspondingly. This work is achieved using Matlab/ Simulink simulation. The effect of some compensation modules is studied such as unified power flow controllers (UPFC) and three types of smart technologies on the performance of the IEEE 9 bus. The traditional PI, is the first controller is utilized in this study that depends on trial and error technique. Second, the controller of Fuzzy logic control (FLC) based trial and error. Finally, the nonlinear auto regressive-moving average (NARMA-L2) based on PI controller. The results show that the controllers used had better improvement in active power and the response of turbine in terms of reduced error for a steady state and ripple reduction in the torque and speed responses. In addition, NARMA-L2 controller presents better results from other methods especially in power output and in terms of reducing the steady state errors of load changes and ripple minimization, making this controller more active to the load and speed variations.

Keywords: Pitch angle, SCIG, PI controller, Fuzzy controller, NARMA-L2 controller

1. Introduction
Nowadays, there is a growing interest in using renewable energies due to some exceptional benefits such as global availability, low initial costs, being environmentally friendly and the high rate of technological development [1]. Wind energy is the most accessible variable source and is one of the fastest growing renewable energy systems. Moreover, wind turbines play a vital role in micro-grids as energy sources and can be considered as an alternative instead of global network [2]. The blade pitch angle control is the most important controller applied in wind turbine in the purpose of getting the desired output power from wind [3]. There exist several reports on blade pitch angle control. Naik et al [4] developed fluctuations comportment of SCIG employment that depended on wind power system to smoothen power output fluctuations by using hybrid PI added FLC controller of pitch angle and SCIG control depended on wind system energy (WSE). They found that the pitch angle of hybrid controller was adequate of fluctuations of the smoothing power comparison with PI controller. Djamel et al [5] used DFIG with UPFC at the time of critical clearing fault in multi-machine power system. The system simulation models were designed using Matlab/Simulink where IEEE 9 buses system. The results obtained showed that, the wind power performance under the effect of UPFC to rise the time fault of critical clearing in power system. Jemaa et al [6] execution appraisal of a wind turbine with
variable speed wind utilizing artificial neural network, Neuro-Fuzzy controllers. They studied two control strategies for maximum point tracking (MPPT) connected to a wind turbine modules system utilizing the (PMSG) in factor speed air wind condition. The system with ANN and ANFLS controllers have been displayed, reproduced and broken down by utilizing Matlab/Simulink.

In this paper, the performance of SCIG is studied and analyzed by pitch angle control, where three controls are suggested and compared together. Firstly PI control, secondly fuzzy logic by trial and error, and finally NARMA-L2 based PI. The system of wind turbine farm is connected with IEEE 9 bus grids with UPFC at normal condition.

2. Power Curve in Wind Turbine
Based on wind turbines working principle, which is presented in Figure 1, the power produced by wind turbines depends mainly on wind speed. The power extracted from aerodynamic is given by the following equation [7][8].

\[ P_w = \frac{1}{2}\rho A V^3 \]  

Where: \( V = \) wind speed (m/s), \( A = \) area swept (m²), \( \rho = \) air density (kg/m³).

Wind energy is converted into electrical energy through wind turbines at a rate not exceeding 59% in accordance with Betz’s law. The energy value obtained from the angle of step of the turbine blades (\( \beta \)) and the blade tip speed ratio (\( \lambda \)) is a function of the power factor in the wind turbines (\( C_p \)). Equation (2) expresses mechanical power of the wind turbine:

\[ P_{tot} = P_w C_p(\beta, \lambda) \]  

Equation (1) to Equation (2), as presented:

\[ P_{tot} = 0.5 \rho A V^3 C_p(\beta, \lambda) \]  

Where \( C_p (\beta, \lambda) = \) coefficient of turbine power, \( \lambda = \) blade tip speed ratio (TSR) and \( \beta = \) angle of blade pitch.

\( C_p \), has shown nonlinear and variable at wind speed in Equation (4)

\[ C_p = 0.5176 \left( \frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{\frac{-21}{\lambda_i}} + 0.0068 \lambda \]  

\( \lambda_i \) in Equation (5) is substituted in Equation (4) that computed \( C_p \).
Blade tip speed ratio is given in Equation (6).

\[
\lambda = \frac{\omega_{rot} R}{V}
\]  

Where, \(\omega_{rot}\) = angular velocity of turbine rotor (rad/s), \(R\) = blade radius (m).

In Figure 2 the coefficient of power (\(\lambda\)) variation curve is given by ratio of the speed of the blade indicates to the various pitch angles.

![Figure 2: A typical \(\lambda\) - \(\lambda\) curve for various pitch angles from 0° to 20°][7].

3. Mathematical Model of Induction Generator

The subsequent equations designate SCIG in the d-q reference frame [9].

\[
\nu_{ds} = -R_s i_{ds} - \omega_s \Psi_{qs} + \frac{d\Psi_{ds}}{dt}
\]  

\[
\nu_{qs} = -R_s i_{qs} - \omega_s \Psi_{ds} + \frac{d\Psi_{qs}}{dt}
\]  

\[
\nu_{dr} = 0 = -R_r i_{dr} - s \omega_s \Psi_{qr} + \frac{d\Psi_{dr}}{dt}
\]  

\[
\nu_{qr} = 0 = -R_r i_{qr} - s \omega_s \Psi_{dr} + \frac{d\Psi_{qr}}{dt}
\]

Equations (7) to (10) show \(q\) and \(d\) signalize the quadrature and direct axis synthesis and \(r\) and \(s\) signalize rotor and stator quantities. The situation of the \(d\) axis coincide with the extreme of the stator flux, that mean the \(\nu_{qr}\) equalize the terminal voltage and \(\nu_{ds}\) equalize zero. The flux linkages can be found utilizing the next collection of equations.

\[
\Psi_{ds} = -(L_{s\sigma} + L_m) i_{ds} - L_m i_{dr}
\]  

\[
\Psi_{qs} = -(L_{s\sigma} + L_m) i_{qs} - L_m i_{qr}
\]  

\[
\Psi_{dr} = -(L_{r\sigma} + L_m) i_{dr} - L_m i_{ds}
\]  

\[
\Psi_{qs} = -(L_{r\sigma} + L_m) i_{qr} - L_m i_{qs}
\]
From equations (7) to (10) and (11) to (14), the voltage, current relation of the SCIG can be derived. When acting this, the stator transient, must be neglected in the upper equations of (7) to (10) cause of the facilitation in power system dynamics simulation. The next voltage current relation results in per unit.

\[
\begin{align*}
\nu_{ds} &= -R_s i_{ds} + \omega_s (L_{s\sigma} + L_m) i_{qs} + L_m i_{qr} \\
\nu_{qs} &= -R_s i_{qs} + \omega_s (L_{s\sigma} + L_m) i_{ds} + L_m i_{dr} \\
\nu_{dr} &= 0 = -R_r i_{dr} + s \omega_s (L_{r\sigma} + L_m) i_{qr} + L_m i_{qs} + \frac{d\psi_{dr}}{dt} \\
\nu_{qr} &= 0 = -R_r i_{qr} + s \omega_s (L_{r\sigma} + L_m) i_{dr} + L_m i_{ds} + \frac{d\psi_{qr}}{dt} \\
\nu_{ds} &= \nu_{ds} i_{ds} + \nu_{qs} i_{qs} \\
Q_s &= \nu_{qs} i_{ds} - \nu_{ds} i_{qs}
\end{align*}
\] (15) (16) (17) (18) (19) (20)

From these equations, it can be deduced that the stator winding only is linked to the network. Using Equations (19) to (20), the reactive and active power drawn from the network or fed into can be found, and utilized in the load flow settlement. Equations (15) to (20) show the electrical part of a SCIG. The mechanical side in a dynamic model must be considered. The next equations give the electro mechanical torque developed using a SCIG.

\[
T_e = \psi_{ds} i_{qs} - \psi_{qs} i_{ds}
\] (21)

The alterations in generator speed that result from a variance in electrical and mechanical torque can be computed by the generator equation of motion.

\[
\frac{da_m}{dt} = \frac{1}{2H_m} (T_m - T_e)
\] (22)

Where, \( T_m \) is the mechanical torque in p.u and \( H_m \) is the inertia constant of the generator rotor.

4. PI Controller
PI controller is the conventional pitch regulator plan is used to organizing the turbine speed to increase the power. For partial load region the pitch angle is fixed to zero also it is activated in the full burden area so that the generator speed is organizing based on the reference values. It also improves the error sensibility and steady state error [10], [11].
PI controllers reduce the error by regulating the process control efforts. There are set control parameter, P stands for proportional and I for integral can produce step response including, the settling time, steady-state error, the value of $K_P$ and $K_I$ gain are set at 5 and 25 respectively, and Figure 3 illustrate the block diagram of PI controller. When the proportion gain increases, the steady state reduces, the over shoot increases and makes the system faster which leads to a decrease to the system stability, also the increase in the integral gain leads to increasing the oscillation, over shoot and eliminates steady state [12],[13].

![Figure 3 block diagram of PI controller [12]](image)

5. Fuzzy Logic Control (FLC)

FLC was first presented by Lotfi Zadeh 1965. The reason for the FLC is to improve the yield by permitting set of membership as opposed to inaccurate amount. It has been observed to be a decent decision for some control applications, as it echo the human control dialectics. It comprises of derivation engine, defuzzifier and fuzzifier. Here, the fuzzifier change the inaccurate amount of the information parameters into fuzzy gathering and base on the fuzzy rules encircled depending on the membership function for a certain parameters of the system and after that, fuzzy yields are procured with the assistance of the inference engine. The submit fuzzy control offer in Figure 4 utilized to locate the pitch angle ($\beta_c$) [14],[15].

![Figure 4 Proposed fuzzy logic based pitch angle controller [15]](image)

Fuzzy logic depends on trial and error tuning method by using Mamdani type, the system utilize FLC appears by block diagram shown in Figure 6. The output and input variables employed to controller the design which expressed by the help of the fuzzy collections utilizing variables of linguistic. Fuzzy collections for power error ($\varepsilon$) are described as: SP (small positive), MP (medium positive), LP (large positive), N (negative), XLP (extra large positive) and XSP (extra small positive). For the power change error ($c\varepsilon$), fuzzy collections are selected such as: PS (positive small), PB (positive big), NB (negative big), NS (negative small) and ZE (zero). Whereas, for the output pitch angle control, six functions are considered as: S (small), M (medium), L (large), ZE (zero), XL (extra large) and XS (extra small). The MFs designed for FLC can be observed in Figure 5.
Control strategies are framed as a set of IF-THEN rules and these are as:

If (e is N) or (ch is NB) then (p is ZE)

Similarly, 35 rules have been defined for all input-output MFs as shown in Table 1.

| Change in Error (ch) | Error(e) |
|----------------------|----------|
|                       | N        | ZE      | XSP    | SP     | MP     | LP     | XLP    |
| NB                   | ZE       | ZE      | XS     | S      | M      | L      |        |
| NS                   | ZE       | ZE      | XS     | S      | M      | L      | XL     |
| ZE                   | ZE       | ZE      | XS     | S      | M      | L      | XL     |
| PS                   | ZE       | ZE      | XS     | S      | M      | L      | XL     |
| PB                   | ZE       | ZE      | S      | M      | L      | XL     | XL     |

6. Artificial Neural Network (ANNs)

ANNs are a data processor system involving of a major number of simple, highly interrelated processor elements designed to simulate neurological processing ability of human brain. An artificial neural network can be explained as a computational system involving of a set of highly interrelated processor elements, called neurons, which processing data as a response to outer catalysts. An ANN is a simplified creation that imitate the signal integral and outset firing conduct of biological neurons used means of mathematical equations. Like their biological counterpart, ANN are linked together by links that limit the current of data between peer neurons[16], [17] [18].

7. NARMAL2 Control

NARMAL2 control reorders the neural network plant pattern, which is prepared and disconnected in group structure. This Neural Network controller (NNC) is alluded as input linearization when the plant...
pattern has a specific structure and it is alluded to as NARMA-L2 control when the plant pattern can be drawing nearer by a similar structure. The major thought of this sort of control is to vary the nonlinear system dynamics elements into direct elements by annulment the non-linear [19].

By the NARMA L2 model, you can get the control:

\[ u(k + 1) = \frac{y_r(k + d) - f[y(k), y(k - 1), ..., y(k - n + 1), u(k - 1), ..., u(k - n + 1)]}{g[y(k), ..., y(k - n + 1), u(k - 1), ..., u(k - n + 1)]} \]

which is realizable for \( d \geq 2 \). The following figure is a block diagram of the NARMA-L2 controller.

![Figure 6](image)

**Figure 6** The block diagram of NARMA-L2 with the reference model and plant [19].

This control can be connected with the recently perceived NARMAL2 plant pattern, as appeared in the accompanying figure:

![Figure 7](image)

**Figure 7** The complete controller system with neural network controller NARMA-L2 [19]

8. Simulation of Squirrel Cage Induction Generator (SCIG)

The farm of wind with six turbines (1.5 MW for each turbine) is associated to (33kV) distribution system sends power to (220kV) network across a (25km 33kV) feeder. Farm of the wind (9 MW) was simulated using three pairs of (1.5 MW) wind turbines. SCIG is used in wind turbine system farm linked to grid IEEE 9 bus. The grid linked 50 Hz directly with stator winding and through wind turbine with variable pitch, the rotor is driven. In order to reduce the output power of the generator, the pitch angle was controlled by the nominal value of winds that exceed the nominal speed (9 m / s).

SCIG speed is slightly higher than the simultaneous power generation speed. The speed varies nearly at 1.005 pu when full load and 1 pu when without load. The wind turbines are equipped with protection systems to monitor speed, voltage and current. Also, a capacitor bank has linked in wind turbines low voltage bus 400 Kvar for every pair of (1.5 MW) turbine to compensate the reactive power take through SCIG.

The mechanical power of the turbine is shown as an assignment of turbine speed to wind speeds at the range (4-10) m/s. The wind speed of 9 m/s is nominal speed that produces the mechanical power (1pu=3 MW). The wind turbine and UPFC are two phase models that provide studies on the type of transient stability in long simulation times.
Where the system was noticed in (20 s), the wind speed employed for all turbines was controlled through blocks "wind 1" to "wind 3". As first, the wind speed was adjusted at 8 m/s then start from (2 s) for "wind turbine 1", the wind speed reaches to 11 m/s of (3 s). Same wind waves were used in turbine 2 and turbine 3, with delays (2 s) and (4 s) respectively. After that when t = 15 s a temporary fault was used with 400V low-voltage stations of "wind turbine 2". The overall equivalent circuit of system is offer in Figure 8. SCIG equivalent circuits of generator and wind turbine were used for simulation and study in this work as shown in Figures 9 and 10.

**Figure 8** equivalent circuit of wind power connected to grid.

**Figure 9** Squirrel cage induction generator wind farm.
9. Results and Discussion

The wind speed employed for all turbines was controlled through blocks "wind 1" to "wind 3". As first, the wind speed was adjusted at 8 m/s then start from (2 s) for "wind turbine 1", the wind speed reaches to 11 m/s of (3 s). Same wind waves were used in turbine 2 and turbine 3, with delays (2 s) and (4 s) respectively. The active power generated beginning rising smoothly for each pair of turbines with wind speed to extend its estimated value (3 MW) at (8s) with PI controller. The absorbed reactive power is growing with the generated active power grow as shown in Figures 11 and 12. Every pair of wind turbine absorbs 1.5 Mvar at nominal power. The total exported power measure at the B10 bus at (11m/s) wind speed (8.94 MW) and absorb a reactive power of 0.809 MVAR as shown in Figures 13 and 14.

**Figure 10** Pitch angle control of wind turbine with (SCIG).

**Figure 11**: Active power generated for each turbine at PI controller

**Figure 12**: Reactive power absorbed for each turbine at PI controller.
Initially, the blades pitch angle was zero degree. The turbine speed would grow from (1.0028 to 1.0047) pu on this time frame. The pitch angle increases from 0 to 8 degree when the output power exceeds (3 MW) to restore the output power to nominal value. The response of turbine to change in wind speed, and rotor speed for each turbine were as shown in Figures 15 and 16.

The generator 1 and 3 exceeds turbine speed due to the pitch angle control continuous adapted to work in stable situation as shown in figure (17) for fuzzy controller, furthermore it can be noted that power generated growing with grow in wind speed. Reactive power increases with active power increase as shown in Figure 18. The rotor speed is response to a change for each turbine as shown in Figure 19.
The total power active and reactive power exported for bus 10 (33 kV) can be seen it increase at rate 9.501 MW and 1.079 MVAR with increasing the wind speed as shown in Figures 20 and 21.

For NARMA-L2 controller it is noted that, the generated active and absorbed reactive power begging growing smoothly together with wind speed to reach its estimated value for every pair of turbines. Observe the generator 1 and 3 exceeds turbine speed due to the pitch angle control continuous adapted to work in stable situation shown in the Figures 22 and 23. After reach wind speed to 11m/s, Figures 24 and 25 show the total exported power taken in the B10 (33kv) bus was 11.63 MW, and absorbed reactive power 1.619 MVAR. Turbine response to the change in rotor speed for each turbine is shown in Figure 26.
The comparison of different active and reactive power controllers at bus 10 at final wind speed 11m/s of the wind turbines conditions are shown in this section. The generated active power and reactive power start growing smoothly together with the turbine speed with three types of control as shown in Figures 27 and 28.

A comparison between different controllers for the active and reactive power of the wind turbines under change of wind conditions are listed in Table 2.
### Table 2: Wind turbines responses to a change in wind speed.

| Type Control      | Rated Power (MW) | Reactive Power(MVAR) |
|-------------------|------------------|----------------------|
| NARMAL2 based PI  | 11.63            | 1.619                |
| FUZZY             | 9.501            | 1.079                |
| PI                | 8.948            | 0.809                |

### 10. Conclusions

This work shows study the SCIG performance with wind turbine and the power system. The behaviour of SCIG simulated using MATLAB/Simulink. A number of controls were applied to control pitch angle for pick up as much as possible power wind. The SCIG performance was presented normal condition. The comparisons between the controls used show that NARMA-L2 gives the best performance to improve turbine work and energy. It is found that the control performance of SCIG is satisfactory at normal grid conditions, where both active and reactive powers were kept in despite of fluctuating of the wind speed and net electrical power supplied to grid was maintained constant.

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