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Pitch Angle Control and Wind Speed Prediction Method Using Inverse Input-Output Relation of a Wind Generation System

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Abstract – In this paper, a sensorless pitch angle control method for a wind generation system is suggested. One-step-ahead prediction control law is adopted to control the pitch angle of a wind turbine in order for electric output power to track target values. And it is shown that this control scheme using the inverse dynamics of the controlled system enables us to predict current wind speed without an anemometer, to a considerable precision. The inverse input-output of the controlled system is realized by use of an artificial neural network. The proposed control and wind speed prediction method is applied to a Double-Feed Induction Generation system connected to a simple power system through computer simulation to show its effectiveness. The simulation results demonstrate that the suggested method shows better control performances with less control efforts than a conventional Proportional-Integral controller.

Keywords: Wind speed generation, Pitch angle control, One-step-ahead prediction control, Wind speed estimation and prediction.

1. Introduction

The use of wind generation has been steadily growing for several decades all over the world. As the wind power capacity increases in a grid, the role of wind farms in power system operation does not remain in supplying clean energy any more. It is required that wind farms should be able to show as high performances as conventional power plants in diverse aspects like voltage and power control, fault ride through ability, etc. [1, 2]. Many researches on this have been pronounced. Protection of wind farms, pitch angle control, active power or frequency control and voltage or reactive power control are related important issues [3-8]. Among them, this paper focuses on pitch angle control to meet output power generation requirement of a wind generator.

The pitch angle control principal can be divided into two modes according to the wind speed level. When the wind speed is lower than the rated value, the control system has to work so that the wind turbine may absorb maximum wind energy. On the other hand, when the wind speed level lies between the rated and the cut off value, the control system has to adjust pitch angle in order for torque input to the generator to be kept at an adequate value in spite of wind speed variations [9. 10].

There have been a lot of research results reported on this problem. In [11], a classical Proportional-Integral controller was designed at an operating point. Predictive control scheme with fuzzy logics [12], a robust controller using inverse dynamics [13, 14], applied H∞ controller [15] and an ANN based PID controller [16] have been applied. [17] and [18] suggested multi-objective control in which both regulation of fluctuations and frequency control are included. A simple inverse control system was applied to this problem, too [19].

There exist a lot of other researches on this problem, most of which have one thing in common; the assumption that the instantaneous wind speed is available. However, the mechanical sensing of wind speed by use of anemometers may increase cost and reduce reliability of wind generation systems. That's why some engineers focused their efforts on sensorless wind generation control [20-24]. These researches considered maximum power extraction in wind turbines. However, the importance of constant power control of a wind farm is increasing as the contribution of wind energy to the grid grows [25]. This may be considered as a guide of the future pitch angle control problems.

In this paper, a pitch angle controller and a sensorless wind speed prediction scheme is suggested. It is known that a small disturbance can be estimated with an acceptable tolerance if we have the inverse input-output relation of a system [26]. This concept is applied to the wind turbine system to estimate one step past wind speed. Using the estimated past wind speed data, the wind speed of the next step is predicted under the assumption that wind speed has a tendency to vary smoothly. And an inverse control scheme is adopted for pitch angel control for output power tracking control. The suggested wind speed prediction and control scheme is applied, through computer simulation, to a simple wind generation system model to

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show its effectiveness.

2. Brief Description of the Controlled System

A wind generation system can be divided into two parts according to the resultant energy type; a mechanical part and an electrical part. The mechanical part includes a wind turbine with blades, a shaft and a gearbox. This part transfers kinetic energy in the wind into rotational energy. The electrical part consists of a generator, converters and other electrical control units. The rotational energy from the shaft is converted into electrical energy here. Even though the arrangement of components is diverse, the basic energy flow is the same as shown in Fig. 1.

Among various types of wind generation systems, a variable speed variable pitch, abbreviated to VSVP system is known to provide better performances in efficiency, less torque pulsations and constant power operation. Actually speaking, the basic idea suggested in this paper is applicable to any kind of wind generation type, however, for simplicity, we would like to focus our attention on the VSVP Double-Feed Induction Generation(DFIG) type systems. A typical VSVP DFIG system is illustrated in Fig. 2.

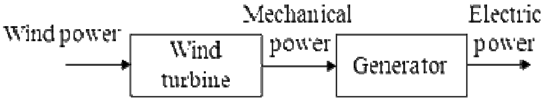


Fig. 1. Energy flow of a wind generation system.

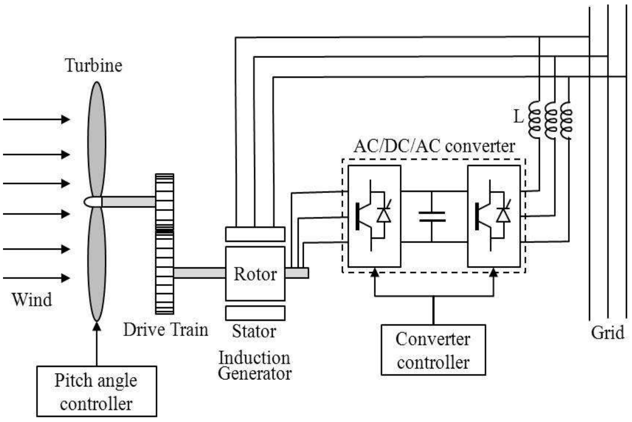


Fig. 2. Schematic diagram of a DFIG wind generation system.

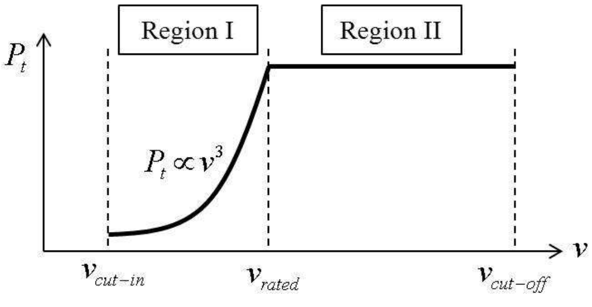


Fig. 3. Curve of output power vs. wind speed.

In general, there exist two different operational regions in a VSVP wind generation system as shown in Fig. 3 [18]. In region I, the wind speed is under the rated value and the wind turbine has to be controlled so that maximum wind energy may be absorbed. On the other hand, in region II, where the wind speed exceeds the rated value, it is required that mechanical torque input to the generator should be kept as constant as possible in order to reduce the fluctuation in the electric output power. This can be realized by pitch angel control, which is the main objective of the suggested control scheme. In this paper, the inverse control scheme is to be applied. We can predict, by use of the inverse input-output relation, the instantaneous wind speed without any anemometer. This is more reliable and economic way of pitch control.

Let's examine the mechanical part in more detail. The mechanical torque provided by the wind turbine is described as [1],

$$T_{wt}=\frac{1}{2}C_p\left(\lambda,\beta\right)\pi R^2\rho v^3, \tag{1}$$

where the torque coefficient C_p is expressed as,

$$C_p\left(\lambda,\beta\right)=c_1\left(\frac{c_2}{\lambda_l}-c_3\beta-c_4\beta^{c_5}-c_6\right)e^{-\frac{c_7}{\lambda_l}} \tag{2}$$

In Eq. (2), parameter λ_l is defined in various ways, among which (3) is an example.

$$\lambda_l=\frac{1}{\dfrac{1}{\lambda+c_8\cdot\beta}-\dfrac{c_9}{\beta^3+1}} \tag{3}$$

The parameters c_1 to c_9 are different for various types of wind turbines. Their typical values can be found in some literatures.

As found in the above discussion, a wind turbine can be considered as a highly nonlinear system. The parameters in Eqs. (2) and (3) are different from an operation condition to another even in a same wind turbine. However, more careful examine reveals a clue which can makes the control problem simpler. The mechanical torque is a function of wind speed, pitch angle and angular speed of the rotor. Besides, the mechanical torque is a one-to-one function of the pitch angle if the wind speed and rotor speed are given. In other words, there may exist a unique value of the pitch angle which results in a specific mechanical torque under the given condition of wind speed and rotor speed.

The electrical part is much simpler to understand. The mechanical torque output of the turbine is impeded by the electrical torque of the generator and the difference between these two values determines the frequency. In this paper it is assumed that any energy storage device is not applied. Another assumption is that the converter set controls the generator to extract maximum active power. The application of an energy storage system makes the problem much more complex. It is expected that a hierarchical control scheme is required and the authors would like to remain this problem as one of the future works.

3. The Proposed Control Scheme

3.1. One-step ahead predictive control

The concept of the one-step ahead predictive control is well defined and utilized in many literatures. It is defined as follows;

$$\begin{aligned}&\textit{Minimize } J=\left(y(k+1)-ref\right)^2+w\left(u(k)\right)^2\\&\textit{subject to } y(k+1)=f\left(\mathbf{y}(k,n),\mathbf{u}(k,m)\right)\end{aligned}\qquad(4)$$

where n and m are appropriate integers decided by the dimension of the controlled system and k is the time index.

In our problem, the output is the electric power and the control input is the pitch angle. In addition, another variable has to be introduced; the wind speed. Even though the wind speed is the basic energy to produce electric power, it is not a controllable variable. Instead, it works as an unknown disturbance. Considering this, the system should be described as;

$$y(k+1)=f\left(\mathbf{y}(k,n),\mathbf{u}(k,m),\ v(k)\right)\qquad(5)$$

Suppose we know the past data of the wind speed $v(\cdot)$.

Then, (5) can be defined as a relation between the output $y(\cdot)$ and the control input $u(\cdot)$. If this relation is a one-to-one mapping between $y(k+1)$ and $u(k)$, the inverse relation of (5) exists, as following,

$$u(k)=g\left(y(k+1),\mathbf{y}(k,n),\mathbf{u}(k-1,m-1),\ v(k)\right)\qquad(6)$$

Note that the time index 'k', in (6), does not mean 'now', but a certain time in the 'past'. We can notice, from (6), that there exists a unique control input $u(k)$ that makes the output reach $y(k+1)$ at the next step, under the given condrtion. In other words, if we replace $y(k+1)$ in (6) with the target value, then the resultant $u(k)$ is the unique control value to make the output reach the target value under the given condition. This is the main concept of the inverse control which is illustrated in Fig. 4.

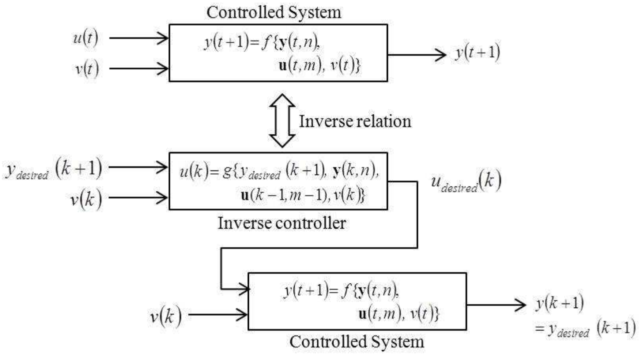


Fig. 4. The inverse control

Now, the questions can be summarized as follows; i) how we can obtain the inverse relation, ii) how we can find the target value of mechanical torque and iii) how we can know the current wind speed.

Question ii) can be solved indirectly if we expand the concept of inverse system to the total wind generation system. The mechanical torque, or similarly, the mechanical power is the input to the generator. In a DFIG, a converter-inverter set controls the electric output power in the manner that the output power is maximized and synchronized with the grid at which the generator is connected. Therefore, we can say that the electric output power is determined by the input mechanical power, in case the converter-inverter set is controlled properly. In other words, we may consider the inverse relation between the pitch angle and the electric output power, instead of mechanical power. In this, the converter control law should not be changed.

On the last question, we may assume a direct measurement of wind speed. However, it is very hard or impossible to measure it precisely in such a short control time step. In this paper, a novel wind speed estimation scheme is suggested using the inverse relation and output error history. This shall be described in more detail in the next subsection.

The remaining problem is the first one. It should be verified, in the first place, whether the controlled system has its sole inverse system, which is a complicated problem. However, in our problem, we can assume that the inverse relation between pitch angle and electric output power exists under the given wind speed condition. A mathematical inverse relation based on an analytic model can be utilized. Otherwise, any other kind of models, e.g., a fuzzy model or an artificial neural network model, can also be used.

3.2 Wind speed prediction using past wind speed data

As mentioned in the previous subsection, current wind speed is required in control of pitch angle. It can be obtained easily using the inverse relation, which shall be explained in this subsection. It is quite reasonable if we assume that the wind speed cannot be changed abruptly in a control interval which is a very short time such as dozens of milliseconds. This assumption enables us to predict the wind speed of the next time by use of past wind speed data.

There are a lot of kinds of candidates which can be applied. In this research, Exponential Smoothing Model (ESM) [27] is utilized, which is a generally known technique that can be applied to time series data, either to produce smoothed data presentation, or to make forecasts. It is commonly applied to financial market and economic data, however it also can be used with any discrete set of data measured in a constant duration. If there exists a trend, double exponential smoothing is adequate and exponential smoothing can take seasonal or periodic change into account. In our problem, there is no need to consider any trend or seasonal periodic change. Therefore, simplest form of ESM is used for wind speed prediction. This method is found, with excessive tests, to be simpler but more effective than moving average methods, without loss of accuracy.

Let's formulate simplest form of ESM. Suppose the wind speed increment at time k is Δv_k, then the wind speed at time k+1 is

$$v(k+1)=v(k)+\Delta v(k) \tag{7}$$

In prediction,

$$v^{pred}(k+1)=v(k)+\Delta v^{pred}(k) \tag{8}$$

What we are to find is $\Delta v^{pred}(k)$, where the subscript 'pred' means 'predicted' value. From ESM formula, we obtain;

$$\Delta v^{pred}(k)=\alpha\Delta v(k-1)+(1-\alpha)\Delta v^{pred}(k-1),\ \text{for } k>1 \tag{9}$$

where α is a smoothing factor whose value lies between '0' and '1'.

Eq. (9) can be translated that the predicted incremental value at time k is a weighted mean of the measured and the predicted incremental values at time k-1. If we let $\Delta v^{pred}(0)=\Delta v(0)$, then Eq. (9) can be rewritten as follows;

$$\begin{aligned}\Delta v^{pred}(k)&=\alpha\Delta v(k-1)+\alpha(1-\alpha)\Delta v(k-2)\\&\quad+\alpha(1-\alpha)^2\Delta v(k-3)+\cdots+\alpha(1-\alpha)^{k-1}\Delta v(0)\\&=\alpha\sum_{j=0}^{k-1}(1-\alpha)^j\Delta v(k-j+1)\end{aligned} \tag{10}$$

From (10), we can find that the past data are 'forgotten exponentially'. In the starting stage, we have no idea about current or past wind speed, therefore, the data may have little meaning. However, as time goes by, the 'meaningless' data at the starting stage are forgotten. After t is equal to k+1, we can calculate the prediction error of wind speed.

$$\begin{aligned}e(k+1)&=v(k+1)-v^{pred}(k+1)\\&=\{v(k+1)-v(k)\}-\alpha\sum_{j=0}^{k-1}(1-\alpha)^j\Delta v(k-j+1)\\&=\Delta v(k)-\alpha\sum_{j=0}^{k-1}(1-\alpha)^j\Delta v(k-j+1)\end{aligned} \tag{11}$$

Therefore, we can notice that the wind speed prediction error is bounded if the incremental wind speed is bounded. This assumption is quite natural. Now, the only remaining problem is 'how we can estimate past wind speed', which shall be described in the next subsection.

3.3. The estimation of past wind speed

In the previous subsection, a prediction method of wind speed is explained. This method requires exact past wind speed data. However, we have no measured data of wind speed because of sensorless scheme of the suggested control method. Instead, an estimation method of past wind speed is proposed in this subsection.

According to the inverse control scheme, we can calculate the optimal input $u_{desired}(k)$ by use of (6) with $y(k+1)$ replaced by $y_{desired}(k+1)$ which is the target value of the output at k+1. In this, current wind speed $v(k)$ is required. If $v(k)$ is exactly the same as the real wind speed at time k, the next output should become the same as its target value. On the other hand, if the wind speed prediction at k+1 is not exact, the next output $y(k+1)$ will be different from its target. The output error is due to the error in the wind speed.

Consider the dynamics of the controlled system and the inverse control scheme again;

$$y(k+1)=f\left(\mathbf{y}(k,n),\ \mathbf{u}(k,m),v(k)\right) \tag{5-1}$$

$$u(k)=g\left(y_{desired}(k+1),\mathbf{y}(k,n),\mathbf{u}(k-1,m-1),v^{pred}(k)\right) \tag{6-1}$$

At time k+1, we can measure the output $y(k+1)$ and then, the result of calculation of (6-1) can be considered as the control input to make the next output be $y(k+1)$ with the wind speed $v(k)$. Therefore, the following relations hold;

$$\begin{aligned}u(k)&=g\left(y_{desired}(k+1),\mathbf{y}(k,n),\mathbf{u}(k-1,m-1),v^{pred}(k)\right)\\&=g\left(y(k+1),\mathbf{y}(k,n),\mathbf{u}(k-1,m-1),v(k)\right)\end{aligned} \tag{12}$$

The only unknown value, among the variables in (12), is $v(k)$, which can be expressed as;

$$v(k) = v^{pred}(k) + \varepsilon_v(k) \tag{13}$$

Then, the second relation of (12) becomes

$$u(k) = g\big(y_{desired}(k+1), \mathbf{y}(k,n), \mathbf{u}(k-1, m-1), \\ v^{pred}(k) + \varepsilon_v(k)\big) \tag{14}$$

If we take Taylor's expansion around $v^{pred}(k)$, the following equation is obtained.

$$u(k) = g\big(y_{desired}(k+1), \mathbf{y}(k,n), \mathbf{u}(k-1,m-1), v^{pred}(k)\big) \tag{15}$$
$$+ \left.\frac{d\, g\big(y_{desired}(k+1), \mathbf{y}(k,n), u(k-1,m-1), v\big)}{dv}\right|_{v=v^{pred}} \cdot \varepsilon_v(k) + \cdots$$

Ignoring the terms including high powers of $\varepsilon_v(k)$, we can find the error in the wind speed as;

$$\varepsilon_v(k) \cong \frac{u(k) - g\big(y_{desired}(k+1), \mathbf{y}(k,n), \mathbf{u}(k-1,m-1), v^{pred}(k)\big)}{\left.\frac{d}{dv} g\big(y_{desired}(k+1), \mathbf{y}(k,n), \mathbf{u}(k-1,m-1), v\big)\right|_{v=v^{pred}(k)}} \tag{16}$$

Note that we have already have the approximated inverse function *g*(•). Then, the resultant wind speed of time *k*, estimated, or equivalently, corrected at time *k*+1 is;

$$v^{est}(k) = v^{pred}(k) + \varepsilon_v(k) \tag{17}$$

There exist a couple of questions here. The first one is whether an approximation function may guarantee the derivative of the original function. It is a hard job to show this precisely. Instead, we can accept it conceptually. Suppose $g(x)$ and $\hat{g}(x)$ denotes the original and approximated inverse relation, respectively. Assume that $\left|g(x) - \hat{g}(x)\right|$ is sufficiently small for all *x*. From the definition of derivative, we have;

$$\left.\frac{d}{dv} g(x)\right|_{x=x_0} \cong \frac{g(x_0) - g(x_1)}{x_0 - x_1}, \tag{18}$$

for a number x_1 close to x_0.

The right hand side can be rearranged as;

$$\begin{aligned} \left.\frac{d}{dv} g(x)\right|_{x=x_0} &\cong \frac{g(x_0) - g(x_1)}{x_0 - x_1} \\ &= \frac{\big(\hat{g}(x_0) - e_0\big) - \big(\hat{g}(x_1) - e_1\big)}{x_0 - x_1} \\ &= \frac{\hat{g}(x_0) - \hat{g}(x_1) - (e_0 - e)}{x_0 - x_1} \\ &\cong \left.\frac{d}{dv} \hat{g}(x)\right|_{x=x_0} - \frac{(e_0 - e_1)}{x_0 - x_1} \end{aligned} \tag{19}$$

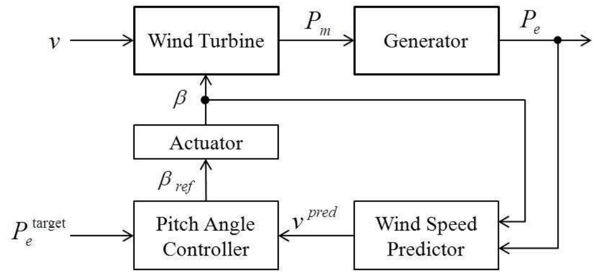


Fig. 5. Overall control scheme

where, e_0 and e_1 are the approximation error at x_0 and x_1, respectively.

The second term of (19) should be sufficiently small from the assumption.

The other question is whether the wind speed error is so small for us to ignore its high power terms. It is not simple to verify it mathematically. However, since the wind speed is changed slowly, considering control interval, we can assume that the prediction error becomes small as time goes by.

In simulation studies, Eq. (16) was applied only when its denominator is larger than a pre-defined small number in order to avoid numerical error arising from dividing some number by too small a number.

The overall proposed control scheme is illustrated in Fig. 5, which is verified through computer simulations in the next section.

4. Simulation Results

The proposed control scheme is applied to a simple power system to show its performances. A 1.5[MW] WT-DFIG with a 500[kW] load is connected to a grid with a generator and an RLC load through 22.9[kV] distribution line. The SIMULINK model of the tested system is illustrated Fig. 6. The three phase source represents an equivalent source of the grid. The data of the wind turbine and generator are tabulated in Table 1.

In the first place, the identification of the inverse relation of the tested WT-DFIG system shall be introduced. Then, we will discuss the suggested control scheme under the two different conditions; the sufficient wind energy condition and the insufficient one. For each case, the wind speed prediction results, pitch angle values and the electric power outputs shall be given to show the performances of the proposed control method.

The simulation results of the proposed control scheme are compared with those of a conventional linearized model-based PI control used in [19]. In PI control application, actual wind speed was directly used because

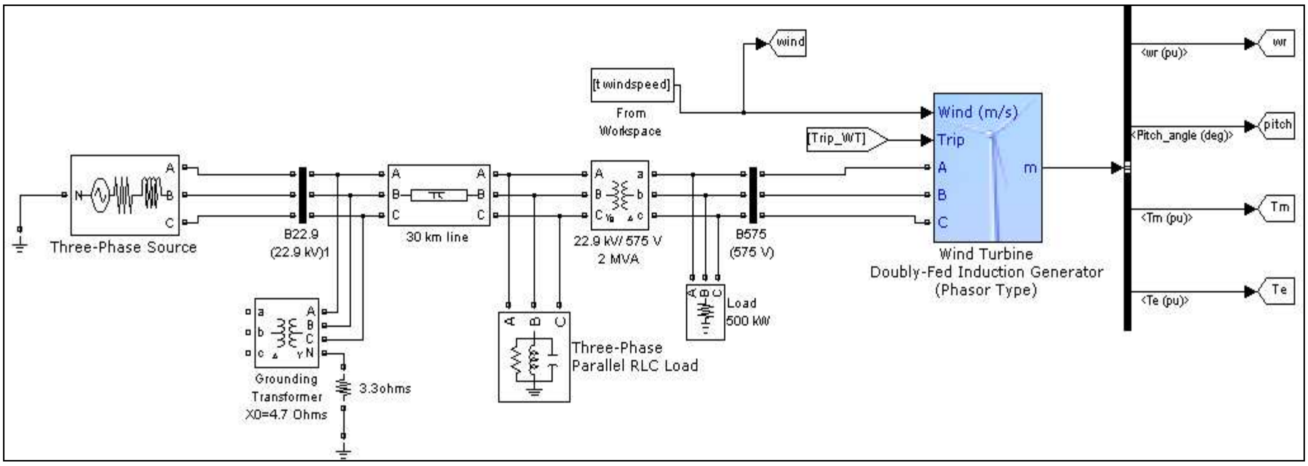


Fig. 6. Simulation system.

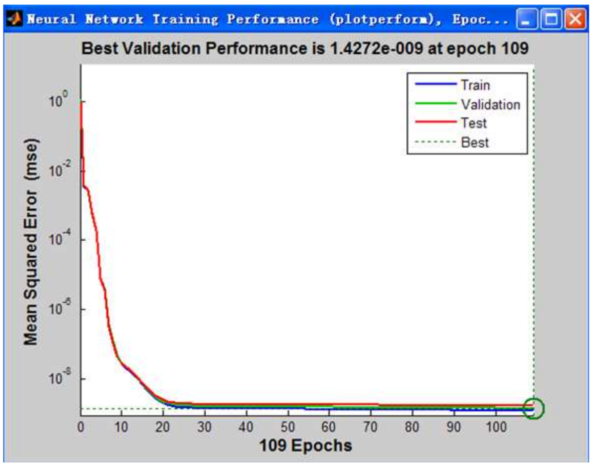
Table 1. Wind turbine and generator data.

Parameters of model	Value
Turbine radius [m]	40
Airdensity [$kg.m^3$]	1.185
Cut-in wind speed [m/s]	3
Cut-out wind speed [m/s]	25
Base wind speed [m/s]	13
Generator pole pairs	3
Generator rated voltage (Vrms)	575
Frequency(Hz)	60
Generator rated power [Mw]	2
Generator moment of inertia[$kg.m^2$]	90
Response time of pitch actuator [s]	0.05

the suggested wind speed prediction method is not applicable. Detailed explanation of PI controller can be found in [19].

4.1 Identifying the Inverse Relations of the WT-DFIG

As mentioned in the previous section, the inverse relation of the WT-DFIG is identified using an ANN. A three-layered Gaussian Radial Basis Function network is used. Because the concept of an ANN is very well known, detailed explanation is omitted here. The training data set is obtained while the pitch angle of the tested system is controlled by a conventional PI controller. Fig. 7 is the identification error of the relation from the electric output power to the pitch angel control value of the tested WT-DFIG system. As expected, the identification of the inverse relation is performed in a successful manner. Since the approximated inverse dynamics model is obtained, we are ready to apply the suggested control and wind speed prediction method.


Neural Network Training Performance (plotperform), Epoc...

Best Validation Performance is 1.4272e-009 at epoch 109

Fig. 7. Learning error of the ANN

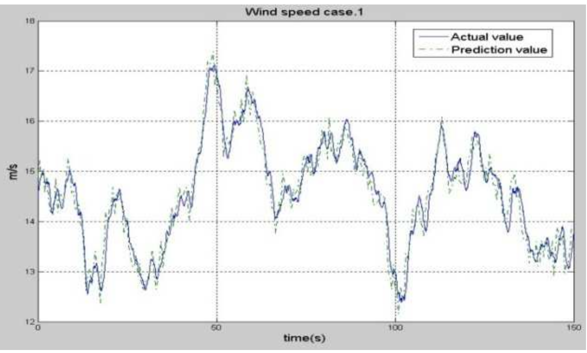


Fig. 8. Wind model and its prediction results for case 1

4.2. Control results of sufficient energy case

The wind pattern considered in this simulation is illustrated in Fig. 8, with its estimated one. Fig. 9 shows the prediction error of this case. As can be seen in this figure, the wind speed prediction error does not approach to ‘0’ as time goes by, however, is remains within a certain small range at every sampling time. Therefore, this method can be considered to be useful to a certain degree of precision. The output power at the terminal is illustrated in Fig. 10, with comparison with the results of a conventional PI controller.

The suggested control scheme shows better tracking performance than a conventional PI controller.

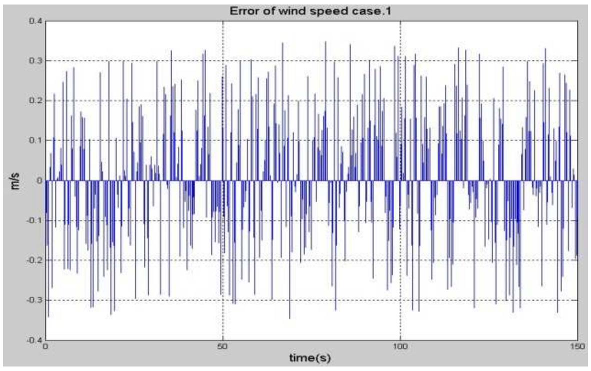


Fig. 9. Wind speed prediction error for case 1

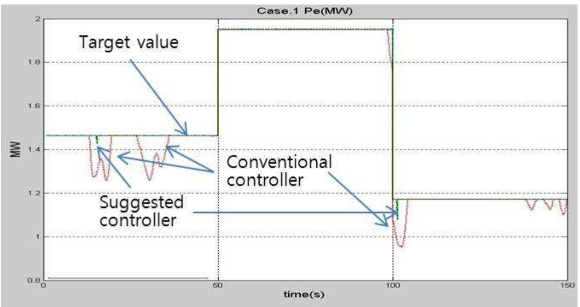


Fig. 10. Output power at terminal for case 1.

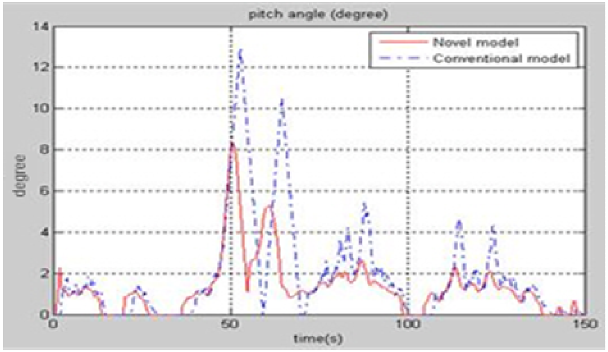


Fig. 11. Pitch angle value for case 1.

Fig. 11 shows the pitch angle position of the two controllers. It can be seen that the proposed control method shows better control results with less control efforts.

4.3 Control results of insufficient energy case

Exactly the same simulations are performed as the previous case. The difference is the wind speed pattern. It is assumed that the wind energy in some intervals is not sufficiently provided that the output power cannot meet the target value. Furthermore, the wind speed variation is supposed to be more frequent than in the previous case.

Figs. 12 and 13 are the wind model and its prediction error. These figures show again that the proposed wind speed prediction method is applicable. Fig. 14 shows the electrical output power.

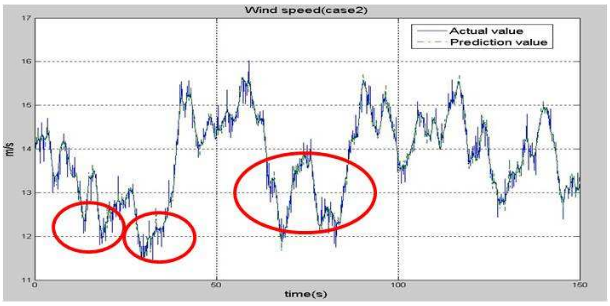


Fig. 12. Wind model and its prediction results for case 2

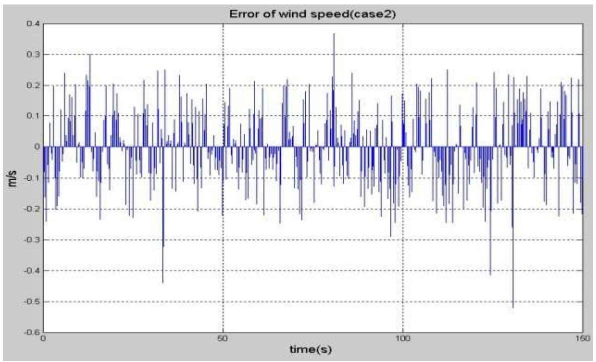


Fig. 13. Wind speed prediction error for case 2

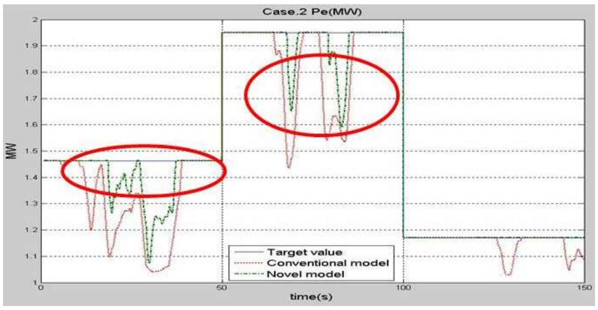


Fig. 14. Output power at terminal for case 2.

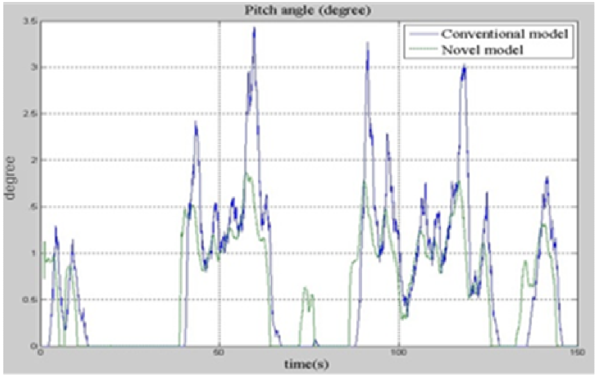


Fig.15. Pitch angle value for case 2.

In Figs. 12 and 14, the circles represent the time interval during which wind energy is not sufficient to produce required electric power. Therefore, during these intervals, the generator cannot provide desired output power even if the blades are moved to the position at which the turbine can absorb maximum wind energy. This can be confirmed if we check the pitch angle values given in Fig. 16. As can be seen in Figs. 15 and 16, the pitch angle stays at ‘0’, the maximum wind energy absorption position, however, the output power cannot reach the desired value. In this case, other power sources have to compensate the shortage. Even in this case, the proposed control scheme shows less output variation with less control effort than a conventional PI controller.

5. Conclusion

This paper proposed a wind speed prediction based sensorless pitch angle control method for WTG systems. One step ahead predictive control scheme using the inverse dynamics of the controlled system is applied to an output tracking control problem. The inverse dynamics is also used in the suggested wind speed prediction method. An artificial neural network is used to approximate the nonlinear inverse input-output mapping between pitch angle and electric power output.

The simulation results show that the suggested control method has the following primary characteristics and implications, as follows.

1. The suggested estimation and prediction method of wind speed is proved to be accurate with sufficiently small error level and useful in active power control.
2. The proposed speed estimation and sensorless control algorithms works well at various operating conditions.
3. The novel control strategy can meet requirements of a WTG system in different operation conditions and is proved, by simulations, to be stable and effective.

The suggested control method can be applied to a constant output power control problem of a large scale wind farm. A hierarchical control scheme of Automatic Generation Control(AGC) of the grid and wind farms combined with wind energy reliability study is one of the future works related with the proposed control scheme.

Appendix

T_{wt} : mechanical torque of a wind turbine
$C_p(\lambda,\beta)$: torque coefficient of a wind turbine
$\lambda = \omega_m R / v$: tip speed ratio
ω_m : angular speed of wind turbine
β : pitch angle of wind turbine
R : radius of wind turbine
ρ : air density
v : wind speed.
$y(k)$: output of the controlled system at time k
$u(k)$: control input at time k
$y_{desired}(k)$: desired output value at time k
$u_{desired}(k)$: control input value to make the output at time k+1 reach the desired value
$\mathbf{y}(k,n)$: n-dimensional output history vector of the controlled system at time k, whose entry is $\left[y(k), y(k-1), \cdots, y(k-n+1)\right]$
$\mathbf{u}(k,m)$: m-dimensional input history vector of the controlled system at time k, whose entry is $\left[u(k), u(k-1), \cdots, u(k-m+1)\right]$
$f\left(\mathbf{y}(k,n), \mathbf{u}(k,m)\right)$: dynamics of the controlled system
$g\left(y(k+1), \mathbf{y}(k,n), \mathbf{u}(k-1,m-1)\right)$: inverse dynamics of the controlled system
$\hat{g}\left(y(k+1), \mathbf{y}(k,n), \mathbf{u}(k-1,m-1)\right)$: approximated inverse dynamics of the controlled system
$v(k)$: wind speed at time k
$v^{pred}(k+1)$: expected wind speed at time k+1, which is predicted at time k
$v^{est}(k)$: estimated wind speed at time k, which is calculated at time k +1
$\Delta v^{pred}(k)$: predicted wind speed variation at time k
$\varepsilon_v(k)$: prediction error of wind speed at time k

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